(Post-Modern)
Large Scale Structure
thru galaxy clustering

Nikhil Padmanabhan
LBNL

Santa Fe Cosmology School 2007

The Guide

- Theory / Modeling
    - P(k) Archaeology
    - The Connection to Galaxies - Large Scales
    - The Connection to Galaxies - Halo Models
- Surveys in Pictures
    - The SDSS in Pictures
- Imaging vs. Spectroscopy
    - Projected density fields
    - The SDSS as a proving ground - LRGs on large scales
    - LRGs on small scales
    - QSO-Galaxy cross correlations
    - Red galaxy merging

Definitions

$$\delta = \frac{n - \bar{n}}{\bar{n}}$$

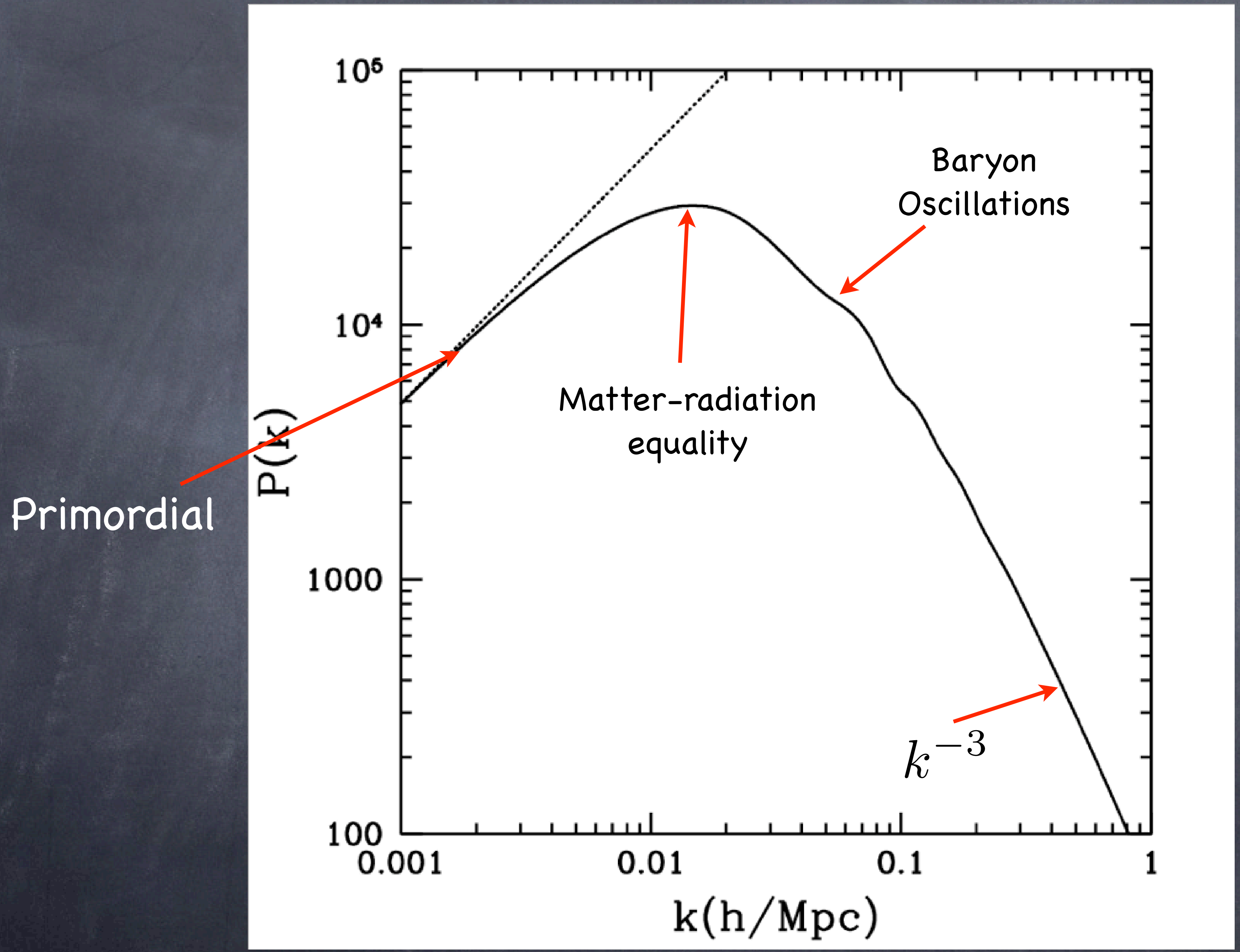
Overdensities, matter or galaxies

$$\xi(\vec{r}) = \langle \delta(\vec{x}) \delta(\vec{x} + \vec{r}) \rangle$$

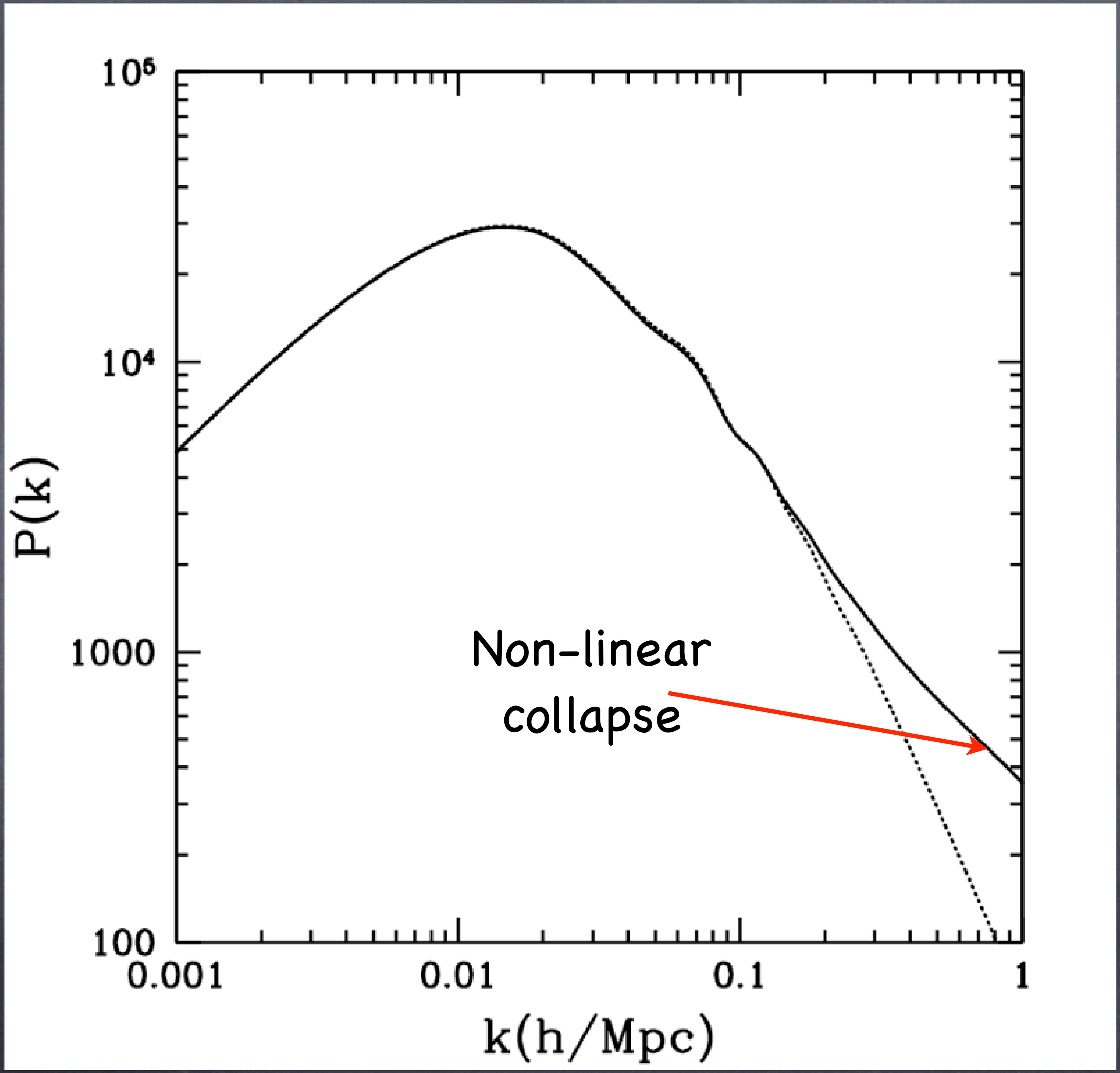
$$P(k) = \mathrm{FT}[\xi(r)]$$

$$\Delta^2(k) = \frac{k^3 P(k)}{2\pi^2}$$

P(k) Archaeology



P(k) Archaeology



Nikhil Padmanabhan

The Connection to Galaxies - I

Traditionally : $P_g = b^2 P_m; \, k < k_{lin}$

Where does this come from?

Assume local bias : $\delta_g(\vec{x}) = f[\delta_m(\vec{x})]$

$$f(\delta) = \sum_{k=0}^{\infty} \frac{b_k \delta^k}{k!}$$

Not necessary, only require hierarchical clustering

Imagine smoothing on scales where $\delta \ll 1$

$$\xi_g = b^2 \xi_m + \mathcal{O}(\xi_m^2)$$

Scherrer & Weinberg, 1998

The Connection to Galaxies - I

$$\xi_g(r) = b^2 \xi(r) + \tilde{\xi}(r)$$

=0 for r > R

FT

$$P_g(k) = b^2 P(k) + c$$

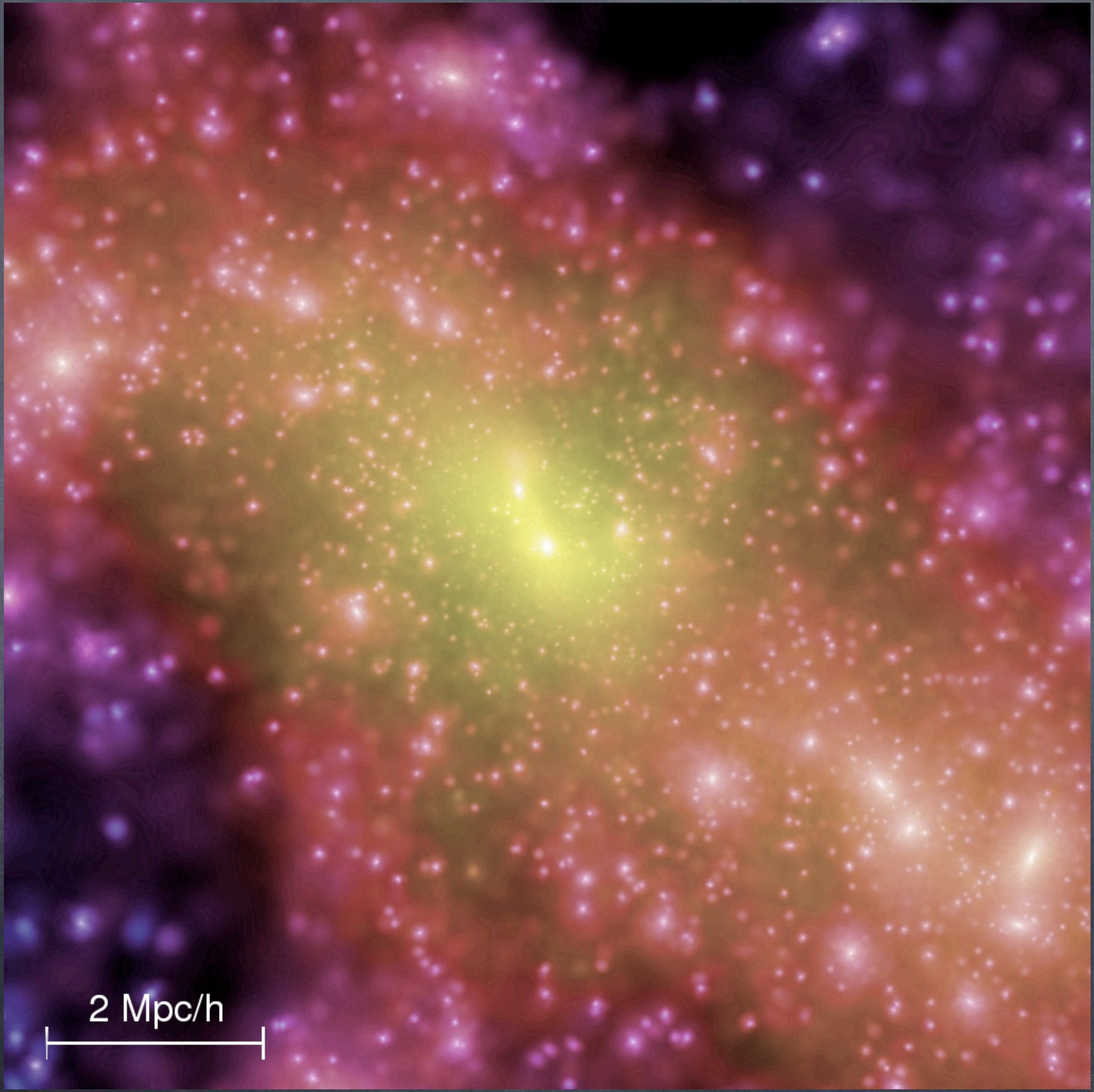
for k << 1/R

shot noise

linear bias

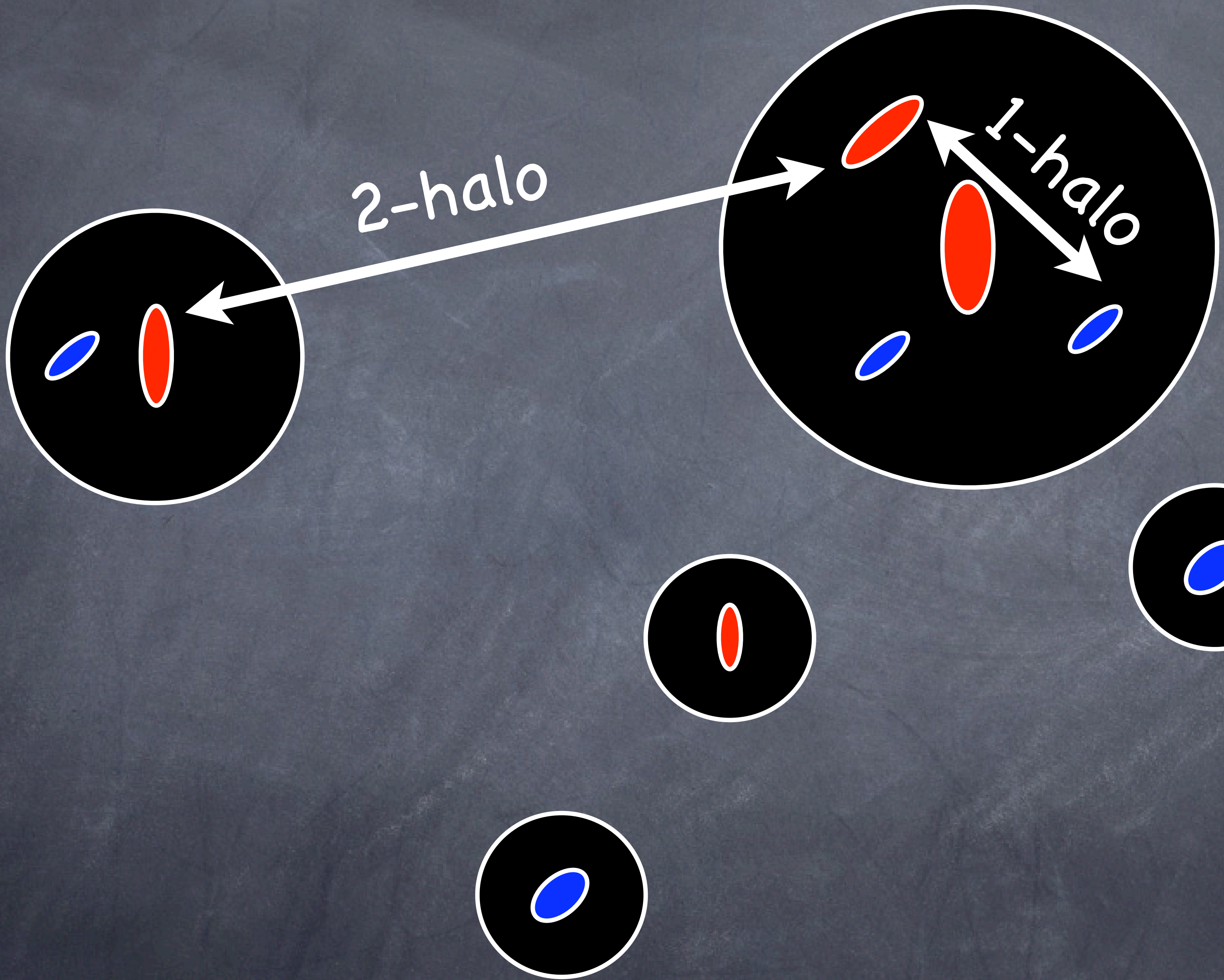
Scherrer & Weinberg, 1998

The Halo Model



Springel et al, Millennium Simulation

The halo model



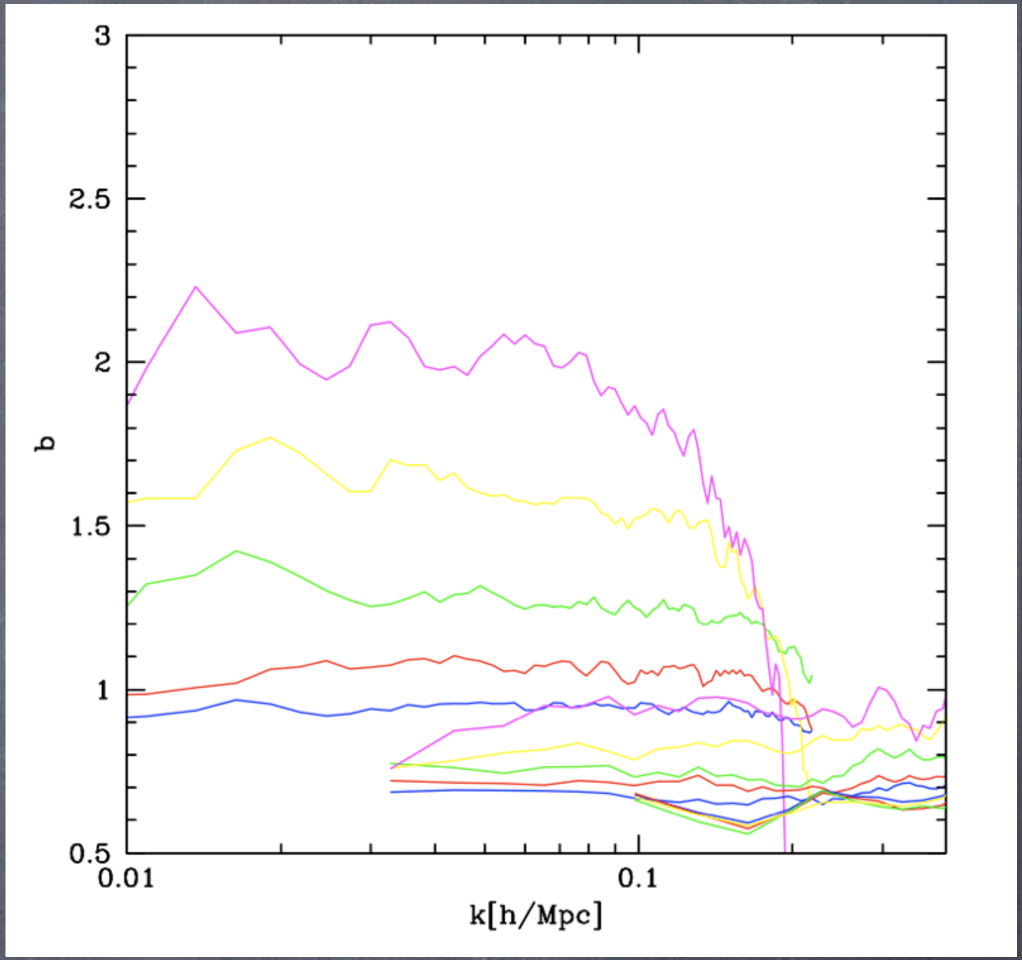
Cooray and Sheth, 2002

The 2-halo term

Halos linearly biased on large scales

Large scale bias is number weighted halo bias

$$P_{hh} \sim \langle b^2 \rangle P_{lin}(k)$$



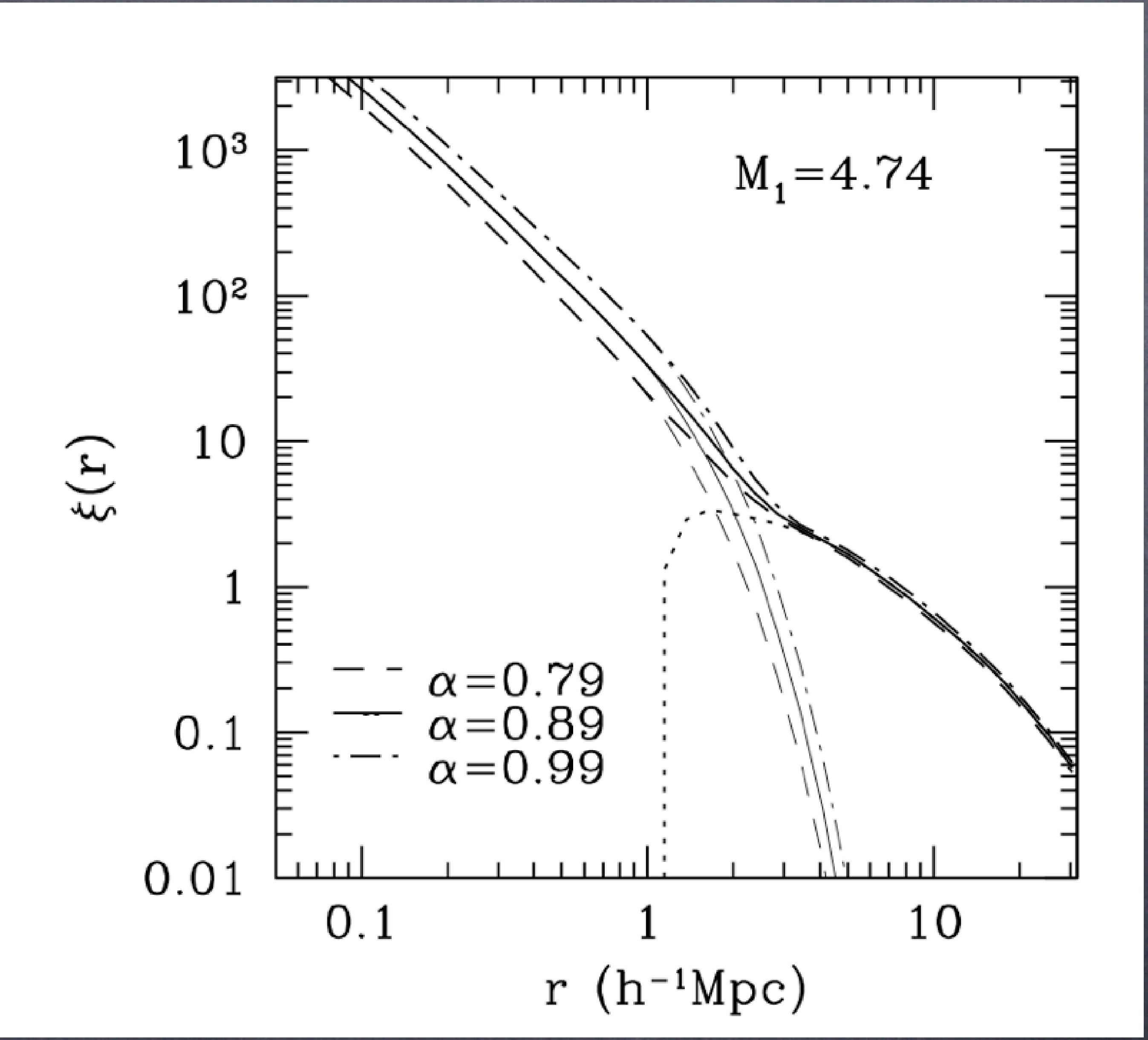
Seljak & Warren, 2004

$$\langle b \rangle \sim \int f(M) b(M) \langle N \rangle (M) dM$$

The 1-halo term

Probe of profile of galaxies in halo

Centrals vs. satellites



Zehavi et al, 2003

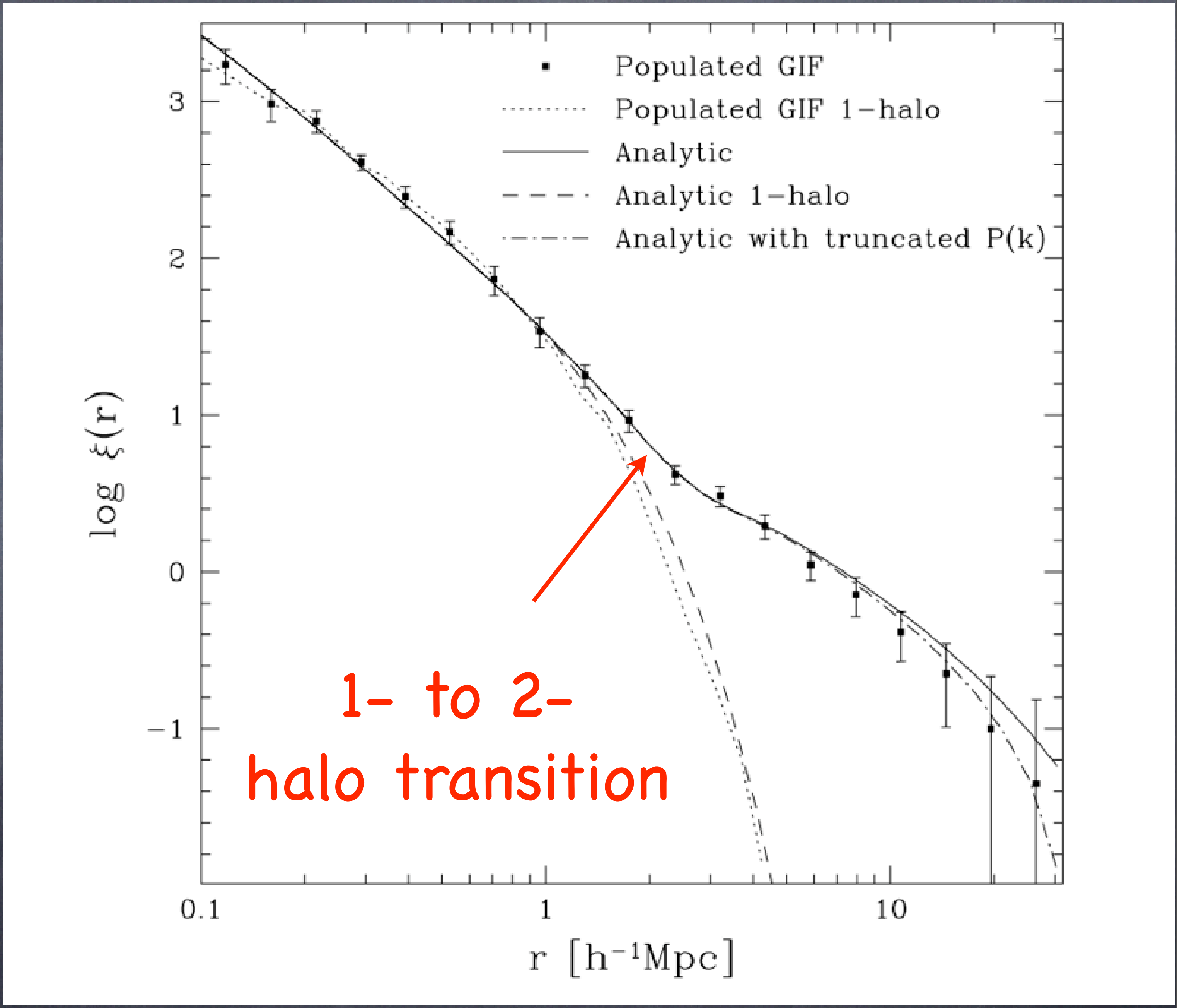
The halo model - all together

Analytic HM

See papers by Zheng, Berlind, Tinker

Numerical HM

Populate N-body simulations with a prescription



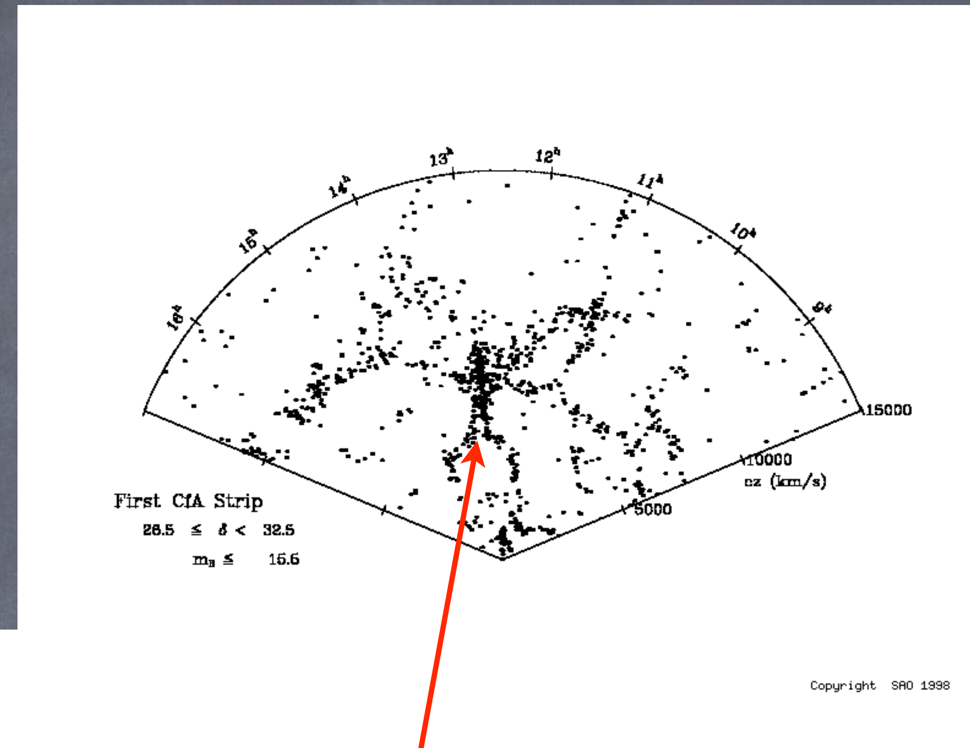
Zehavi et al, 2003

The Guide

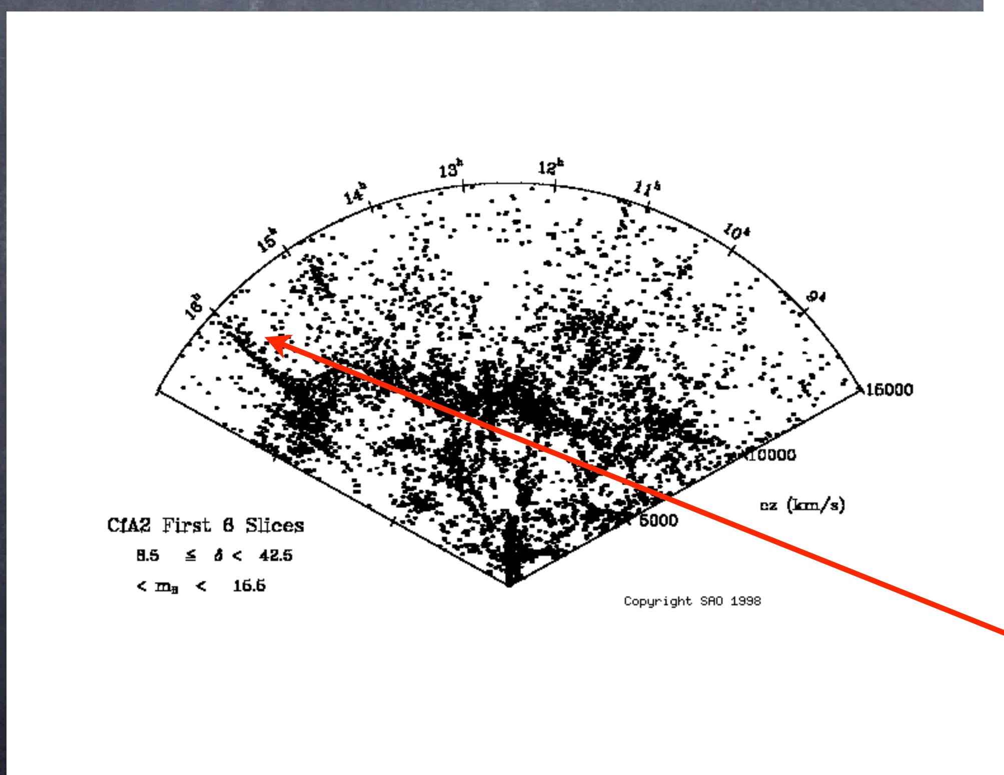
- Theory / Modeling
  - P(k) Archaeology
  - The Connection to Galaxies - Large Scales
  - The Connection to Galaxies - Halo Models
- Surveys in Pictures
  - The SDSS in Pictures
- Imaging vs. Spectroscopy
  - Projected density fields
  - The SDSS as a proving ground - LRGs on large scales
  - LRGs on small scales
  - QSO-Galaxy cross correlations
  - Red galaxy merging

CfA

- Huchra, Davis, Latham, Tonry, 1983
- ~18,000 galaxies (CfA2)



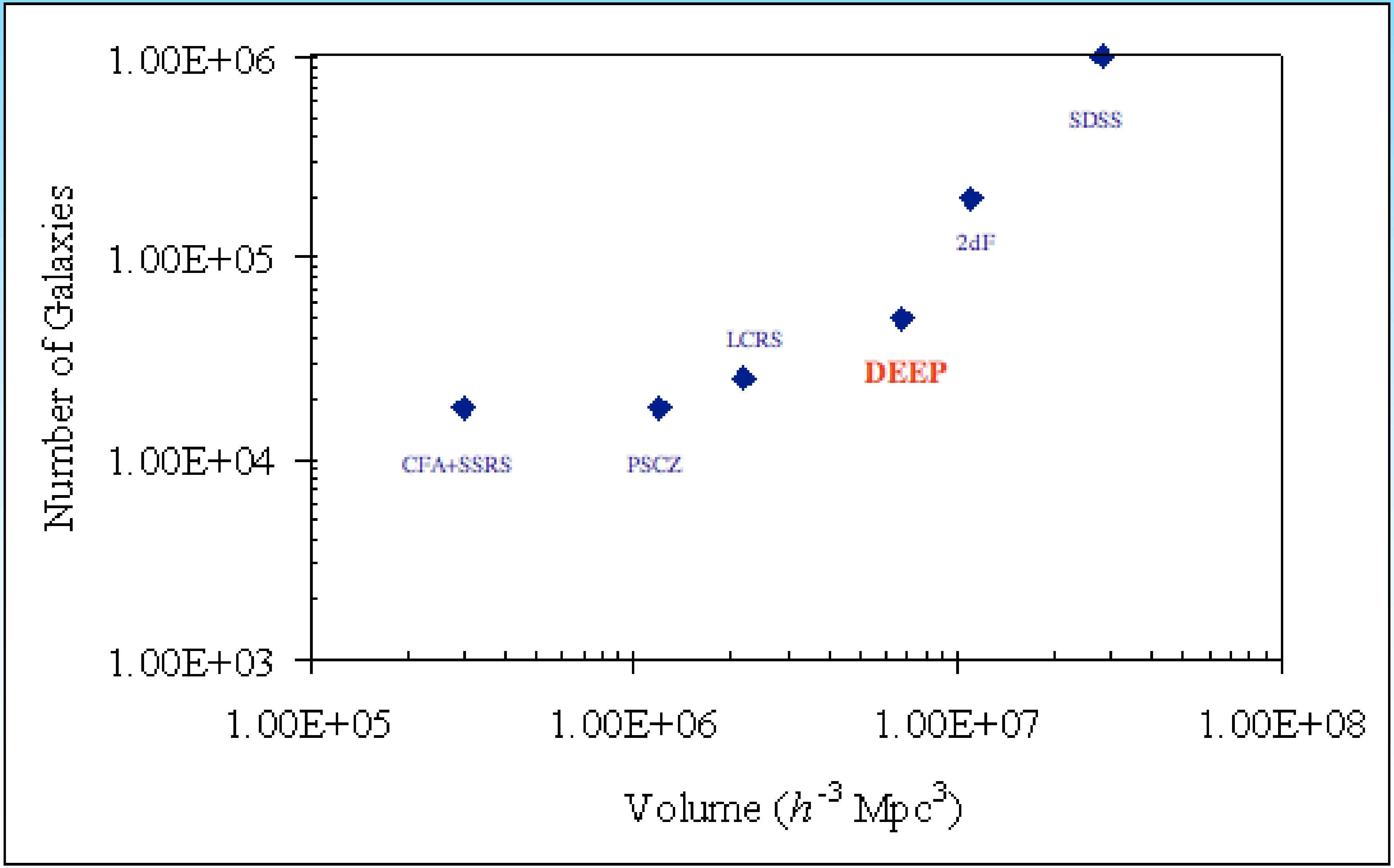
The Stick Man



Fingers of God

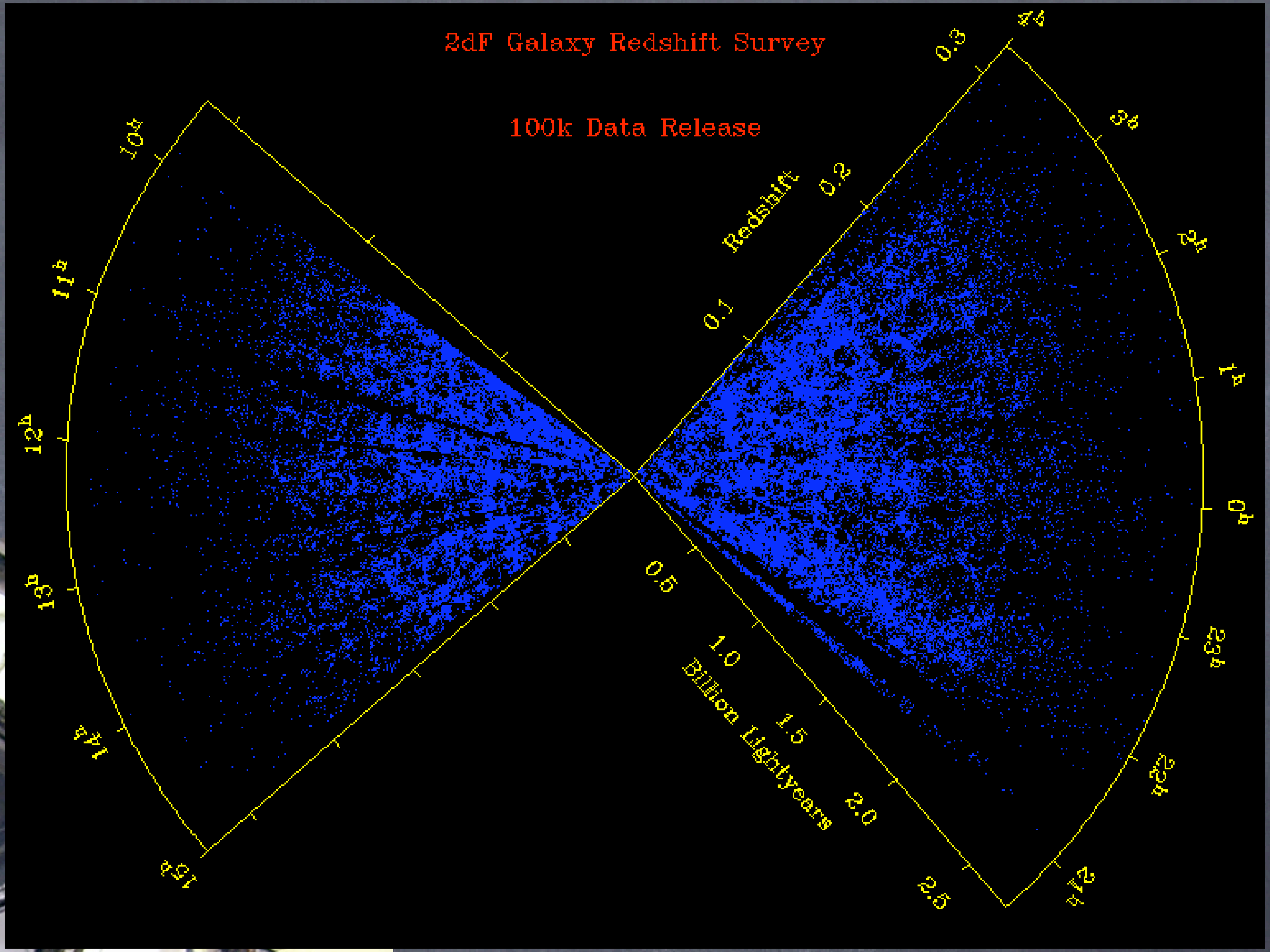
BERKELEY LAB

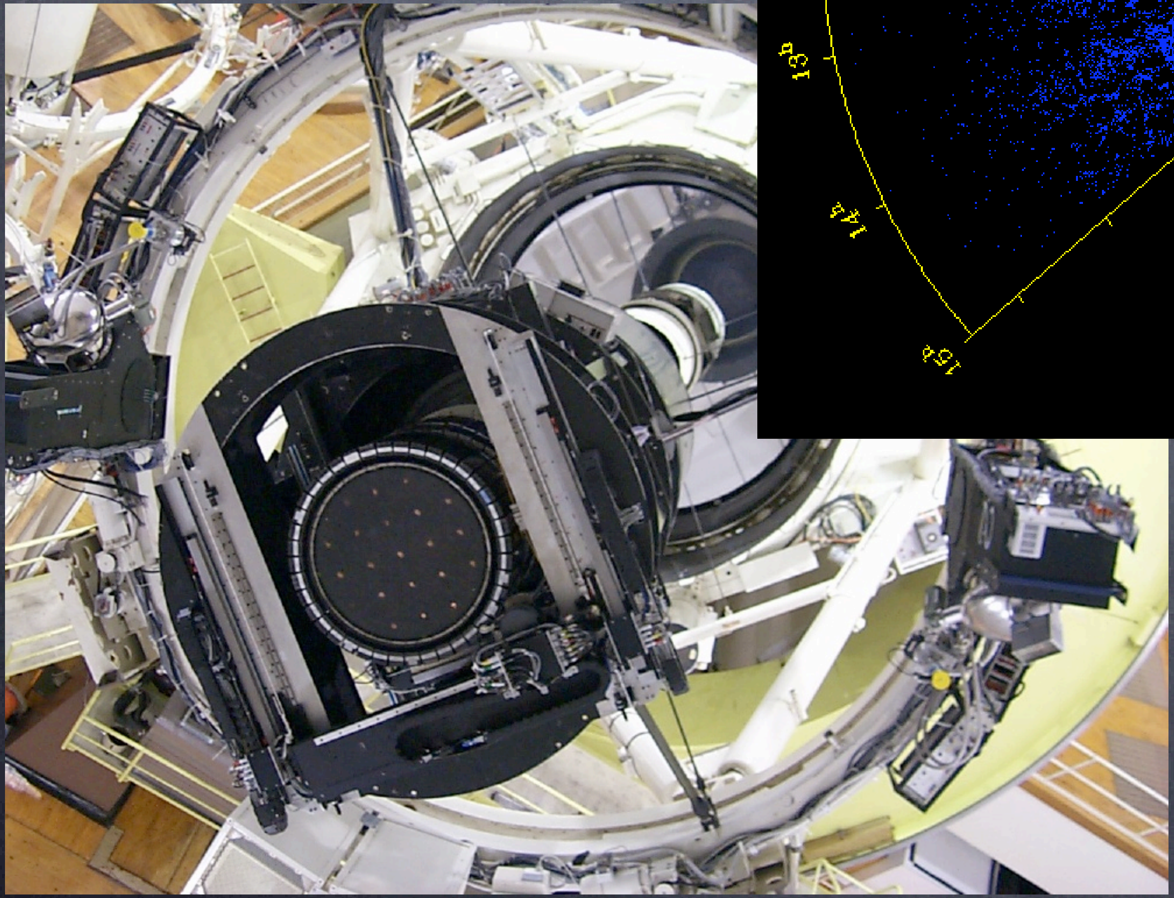
Comparison of redshift surveys



From Marc Davis

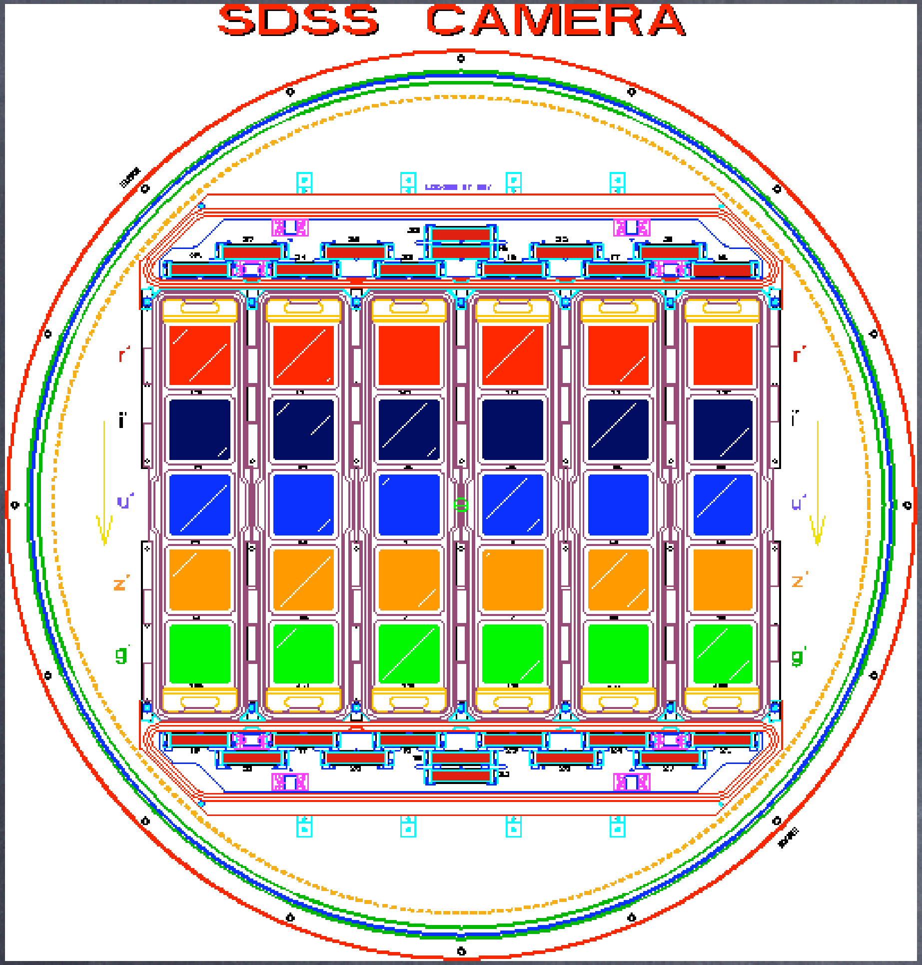
2dF


2dF Galaxy Redshift Survey
100k Data Release
Redshift
0.1
0.2
0.3
0.5
1.0
1.5
2.0
2.5
Billion Lightyears
10h
11h
12h
13h
14h
15h
4h
3h
2h
1h
0h
23h
22h
21h

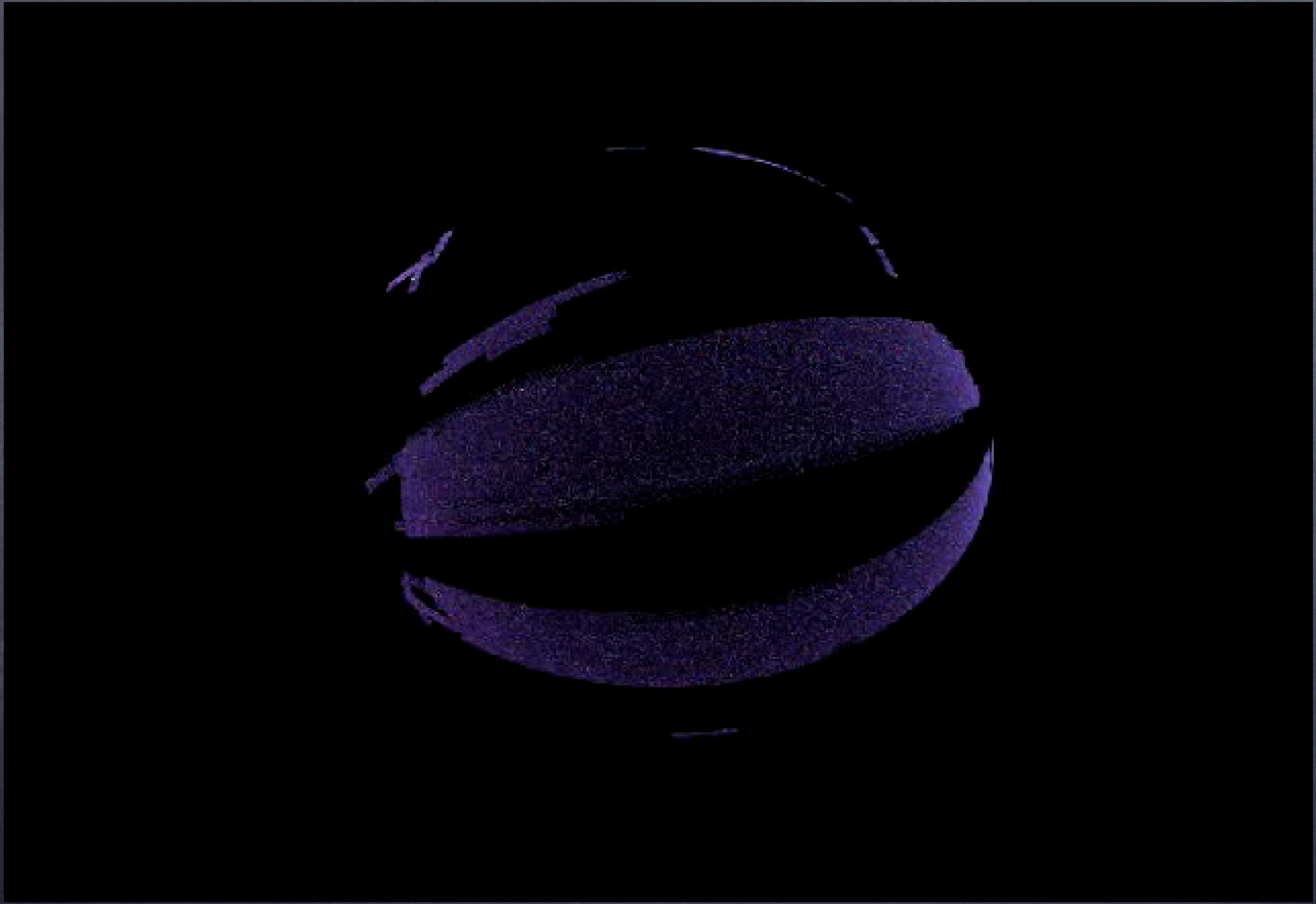


Apache Pt., NM.

SDSS Hardware



6 columns x 5 filters



Observing 101 (at 9 degrees)

DR6 is out!!

SDSS Data Release 6

Sloan Digital Sky Survey

The Sloan Digital Sky Survey (see www.sdss.org for general information) will map one-quarter of the entire sky and perform a redshift survey of galaxies, quasars and stars. The DR6 is the sixth major data release and provides images, imaging catalogs, spectra, and redshifts for download. It is the first data release of SDSS-II, an extension of the original SDSS consisting of three subprojects: Legacy, SEGUE and a Supernova survey. The first public data release from the Supernova Survey is available at www.sdss.org/drsn1/DRSN1_data_release.html

About DR6 explains what is new in DR6, and lists remaining or new caveats and subtleties in the data.

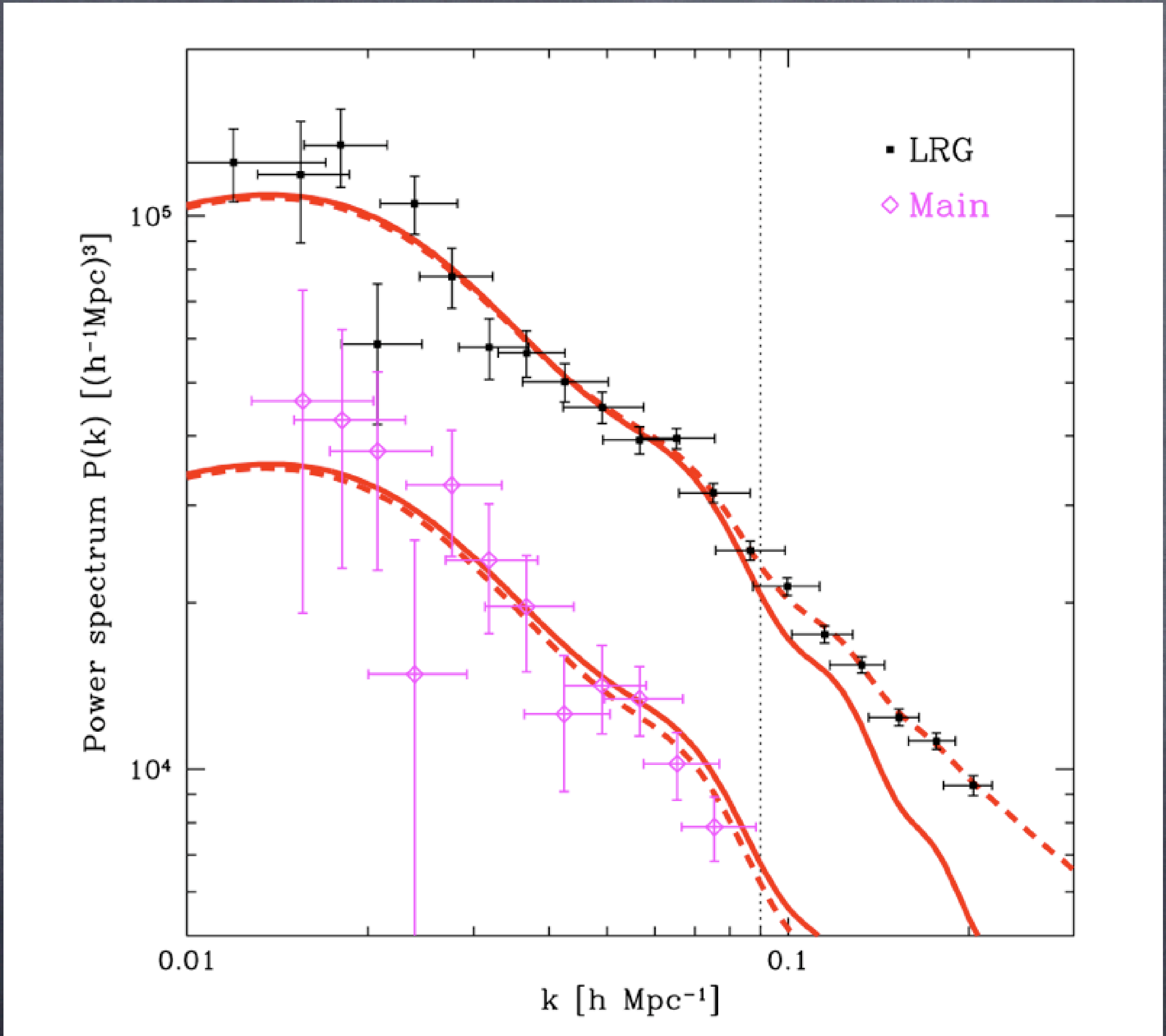
Please refer to the credits page for our sources of funding, participating institutions, and how to acknowledge the use of SDSS data in your publications. Please also note how to refer to SDSS sources in your publications using the proper IAU nomenclature for SDSS sources.

Imaging

Footprint area	Total: 9583 sq. deg. Legacy: 8417 sq. deg. SEGUE: 1166 sq. deg. Supernova Survey: ~300 sq. deg., repeated >40 times M31 / Perseus scan: 26 sq. deg.
Imaging catalog	287 million unique objects (SEGUE: 57 million, Legacy: 230 million)
Data volume	images: 10.0 TB catalogs (DAS, fits format): 2 TB catalogs (CAS, SQL database): 4 TB
Average wavelengths and magnitude limits (95% detection repeatability for point sources)	*u*: 3551Å, 22.0 *g*: 4686Å, 22.2 *r*: 6165Å, 22.2 *i*: 7481Å, 21.3 *z*: 8931Å, 20.5
PSF width	1.4" median in *r*
Pixel size	0.396"
Exposure time for each pixel	53.9 s
Photometric calibration	Regular CAS and DAS: *r* 2%, *u-g* 3%, *g-r* 2%, *r-i* 2%, *i-z* 3% Only Ubercal table in CAS: *r* 1%, *u-g* 2.2%, *g-r* 1.5%, *r-i* 1.5%, *i-z* 1.5%
Astrometry	< 0.1" rms absolute per coordinate

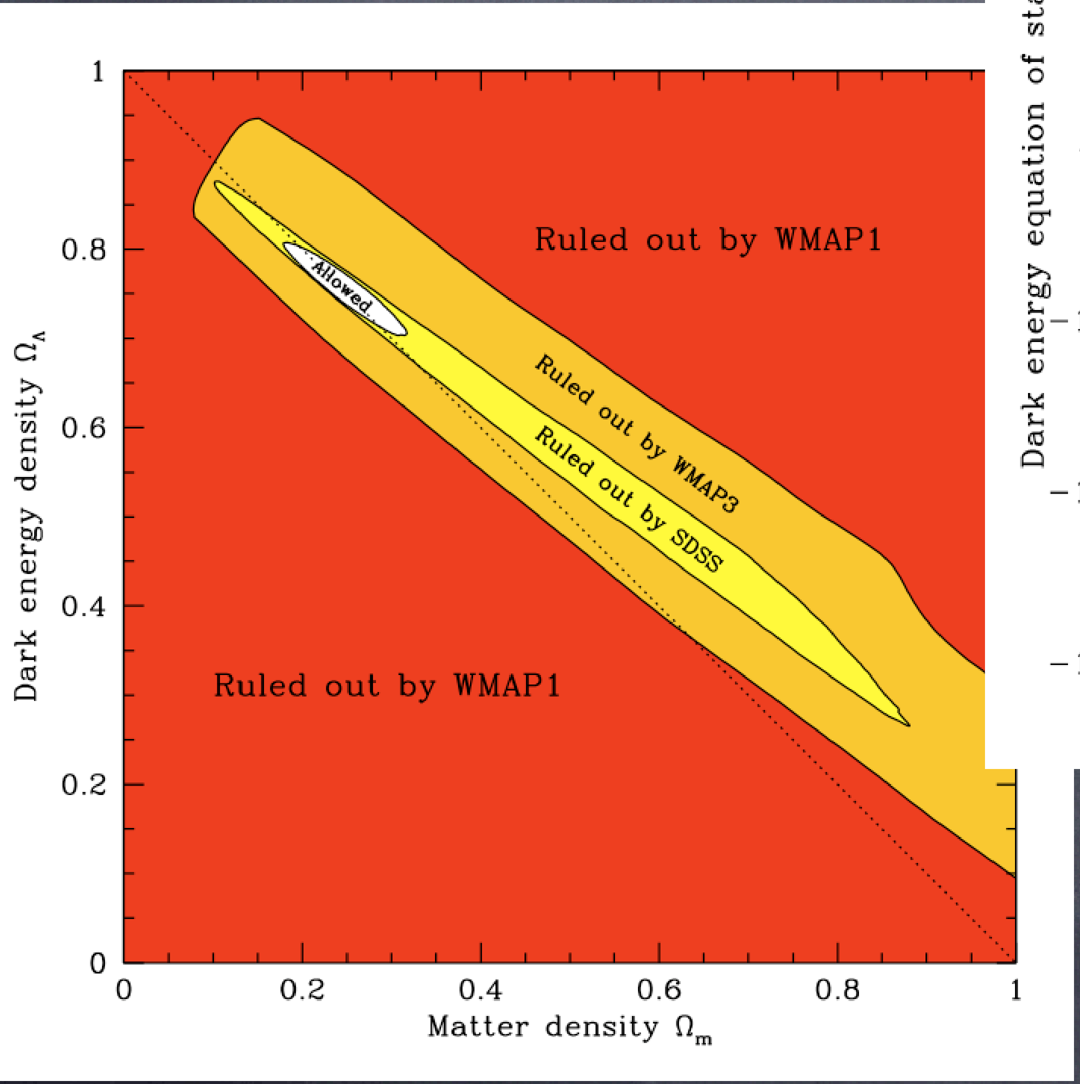
Spectroscopy

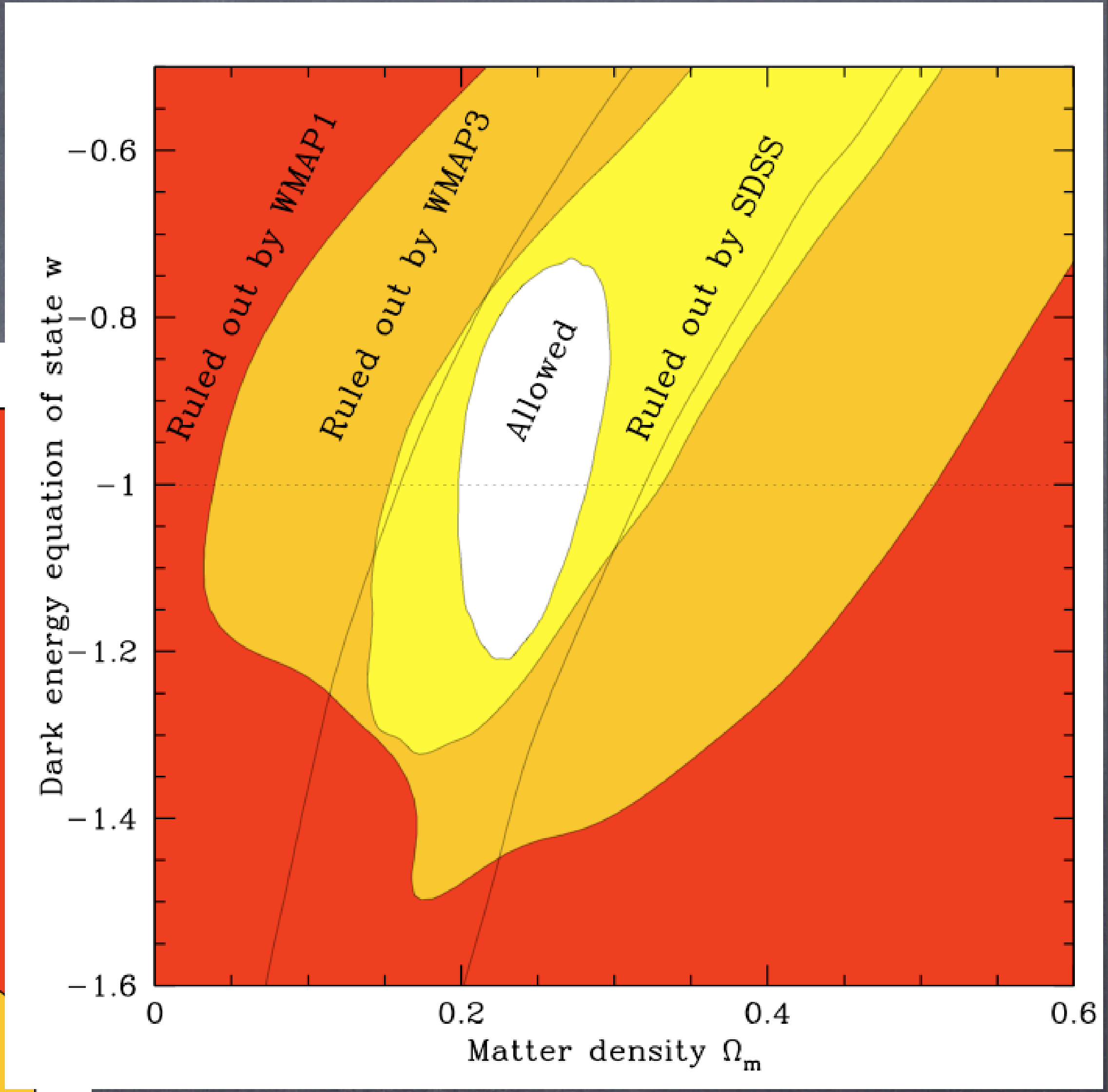
The SDSS LRG P(k)



Tegmark et al, 2006

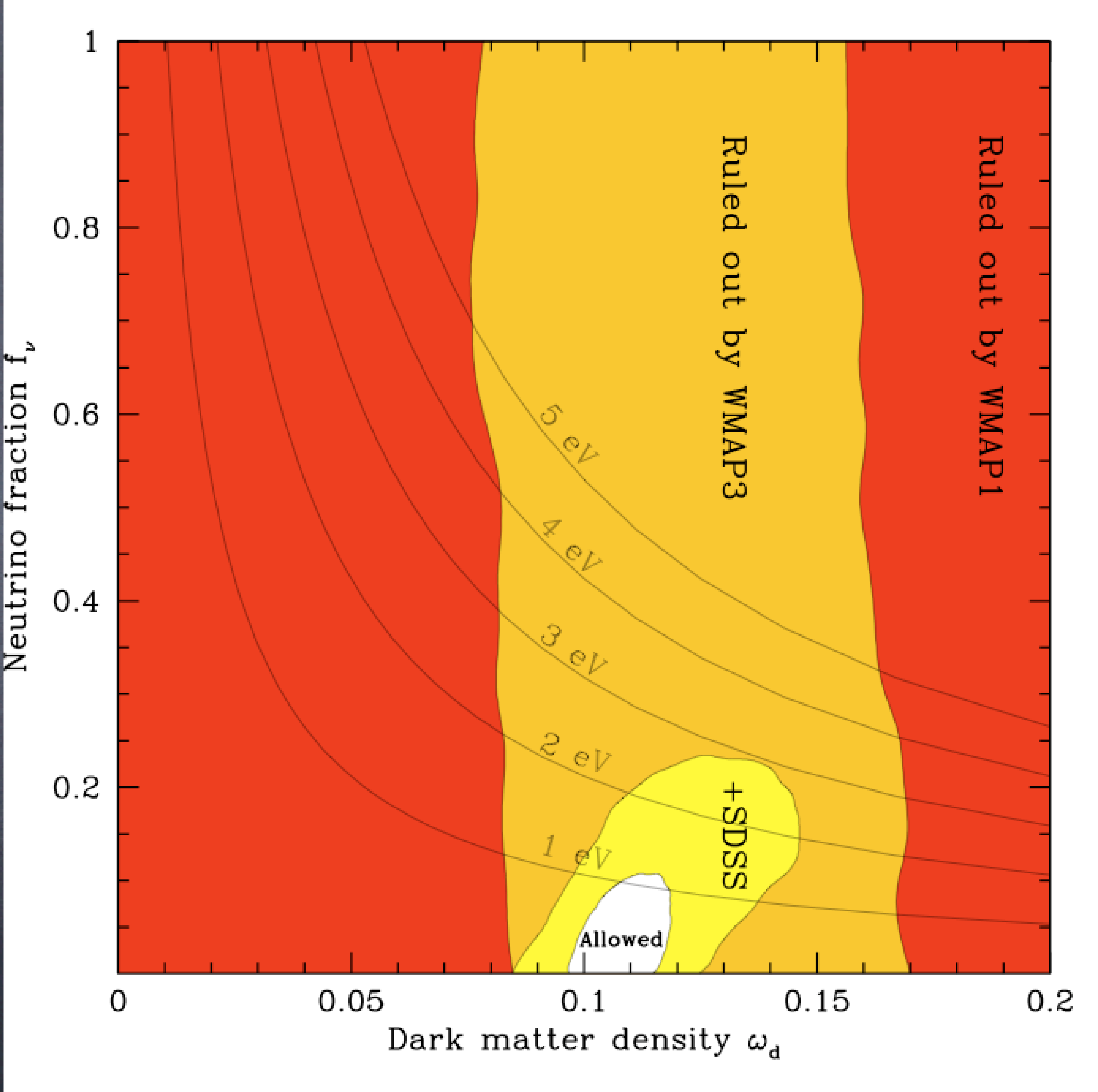
Dark Energy





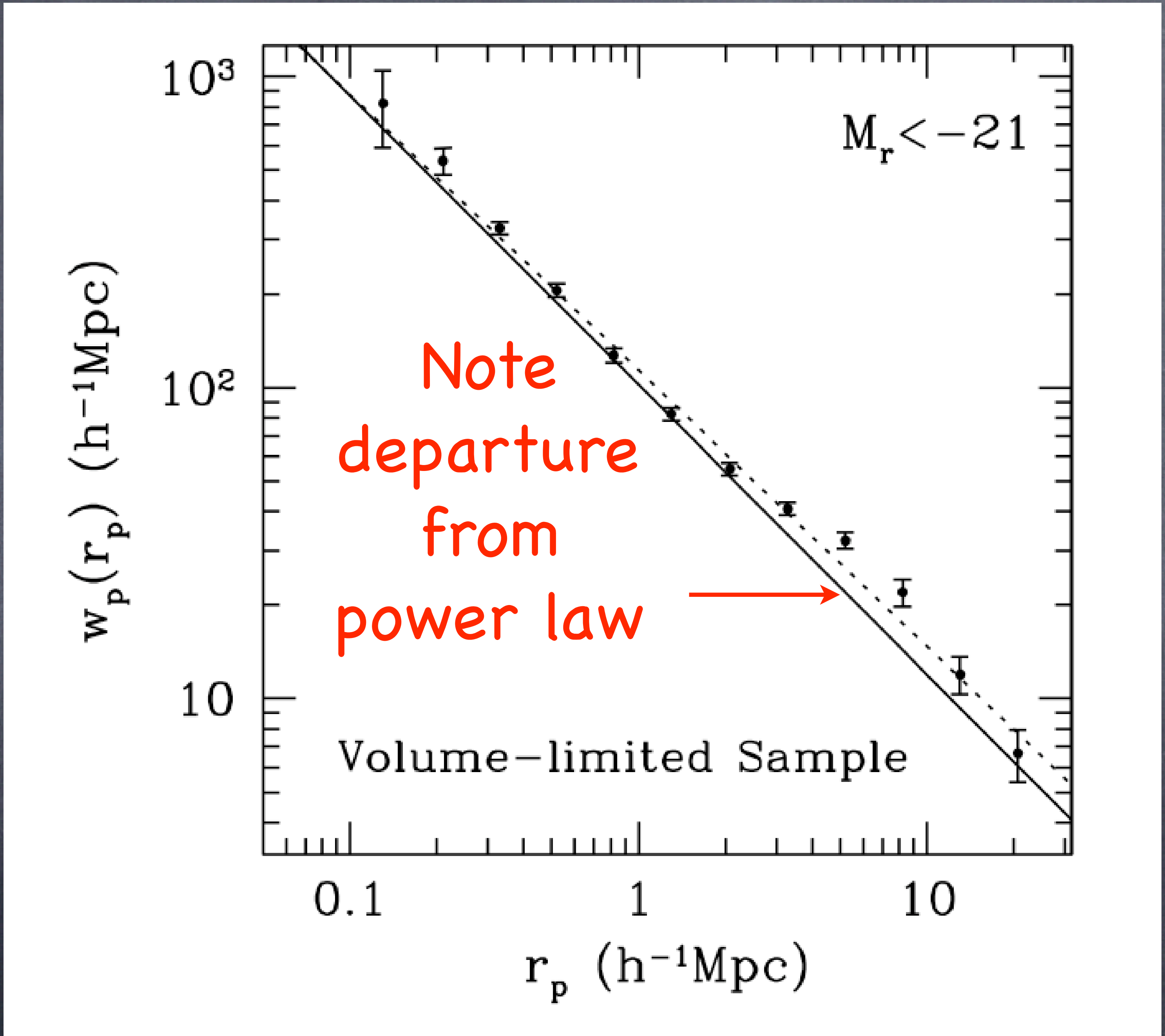
Tegmark et al, 2006

Neutrinos



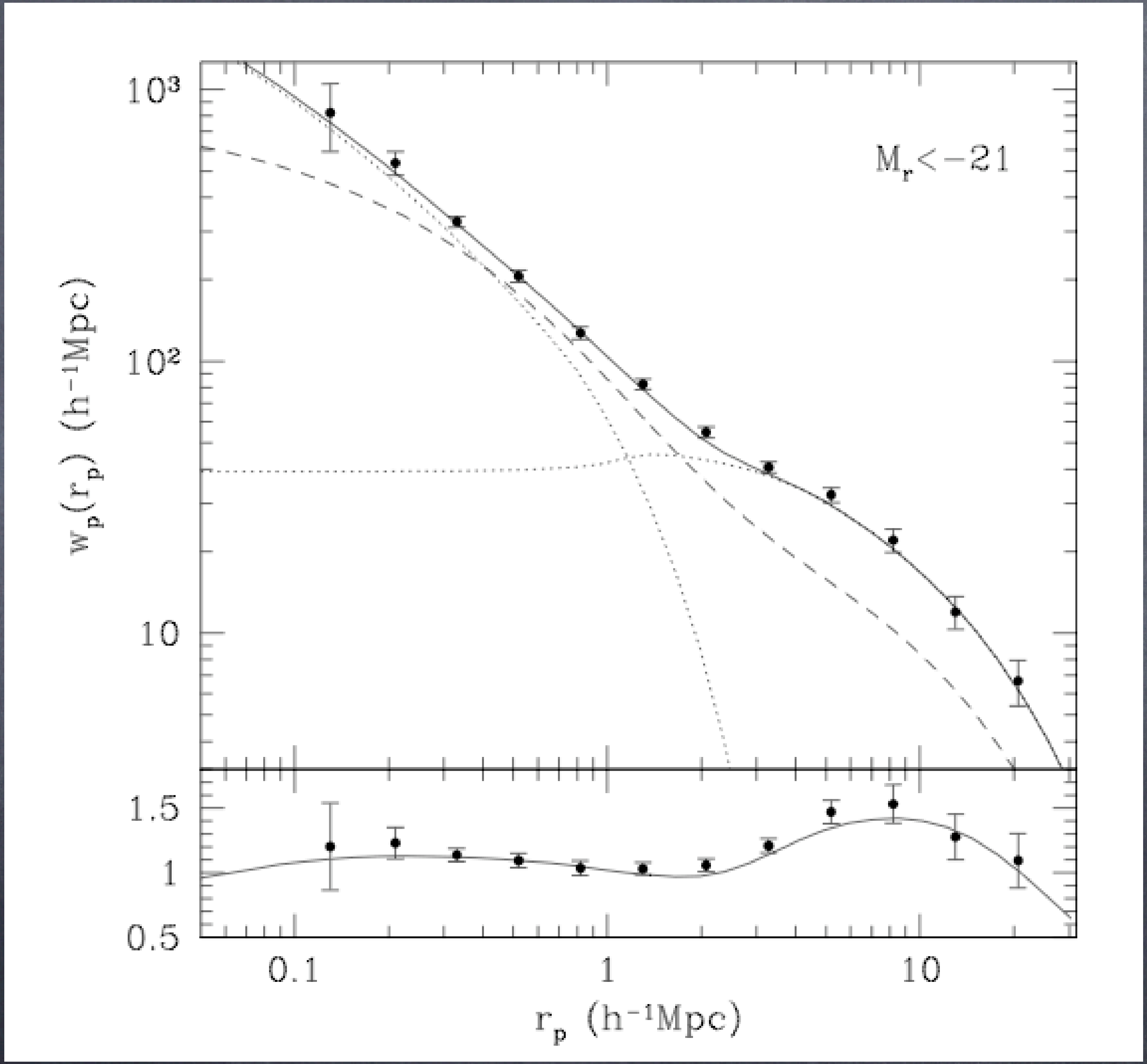
Tegmark et al, 2006

The Galaxy AutoCorrelation



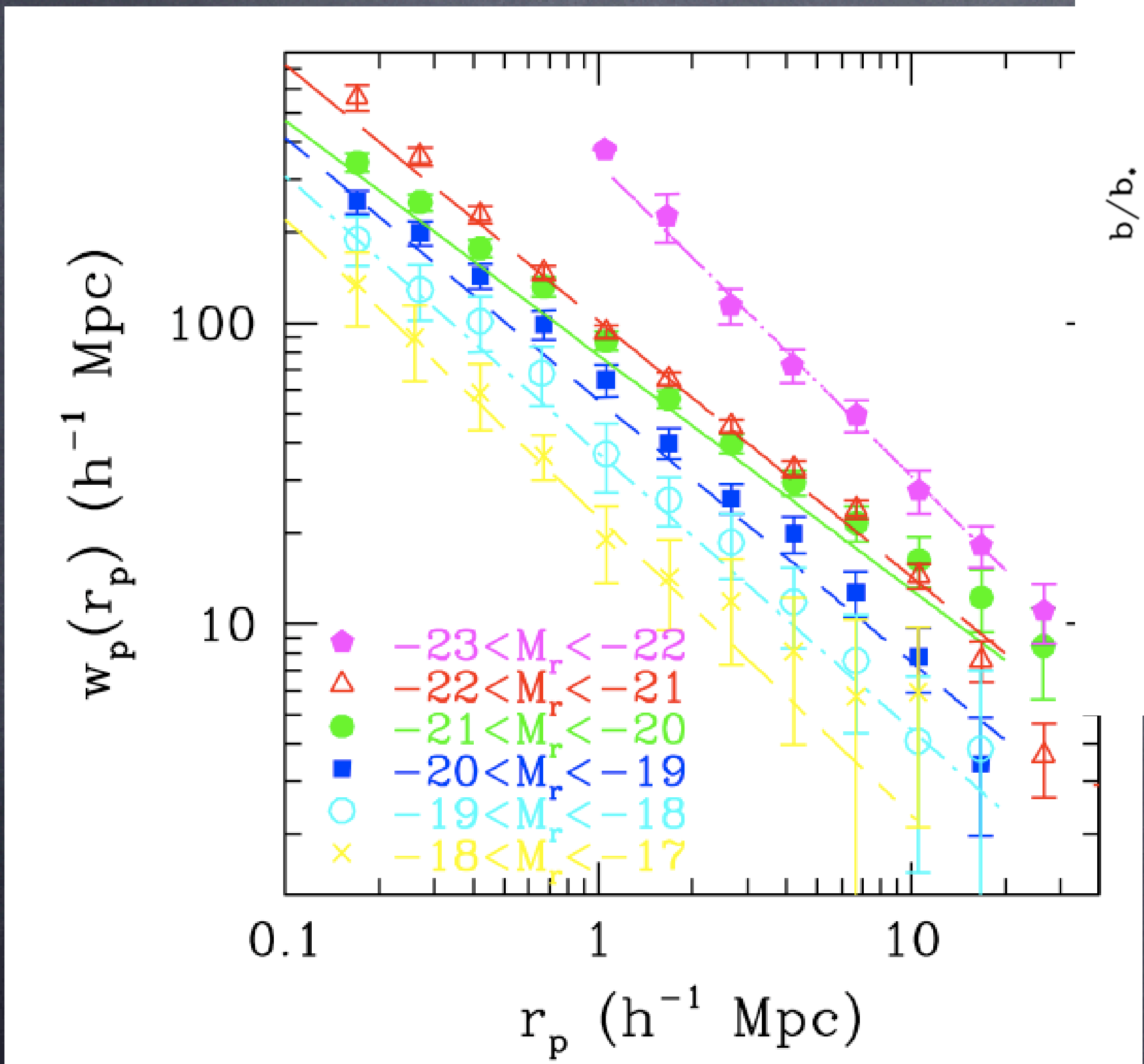
Zehavi et al, 2003

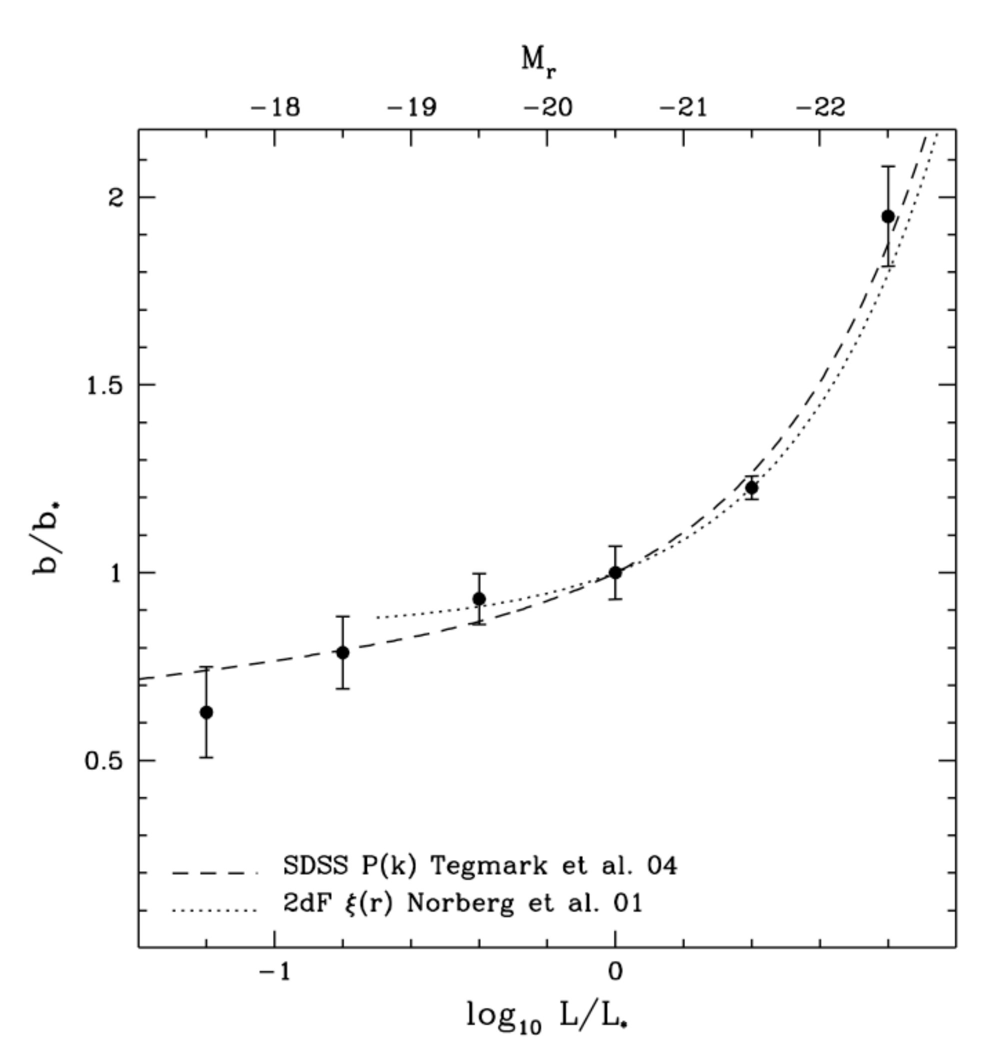
The Galaxy AutoCorrelation



Zehavi et al, 2003

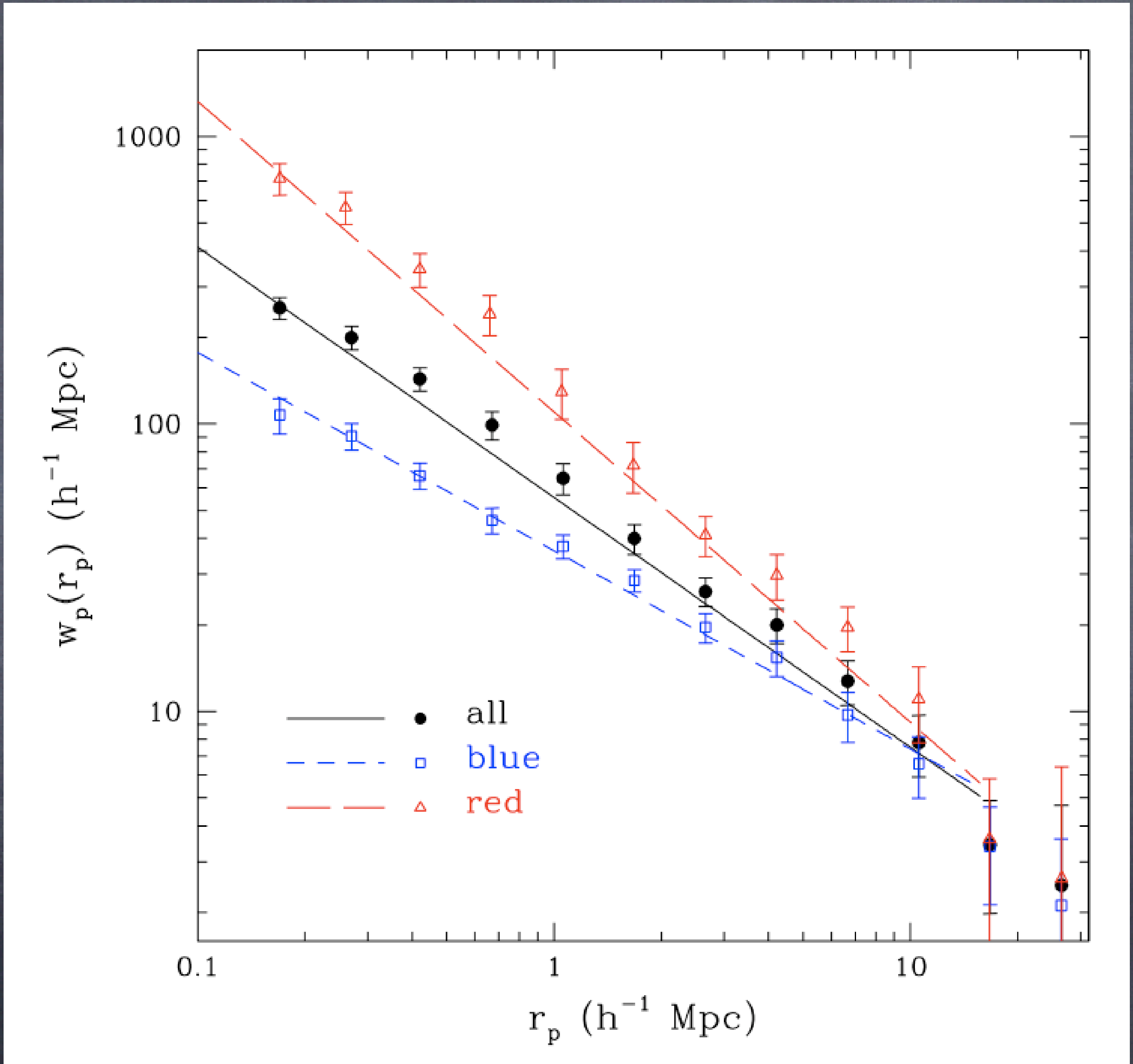
as a fn. of luminosity





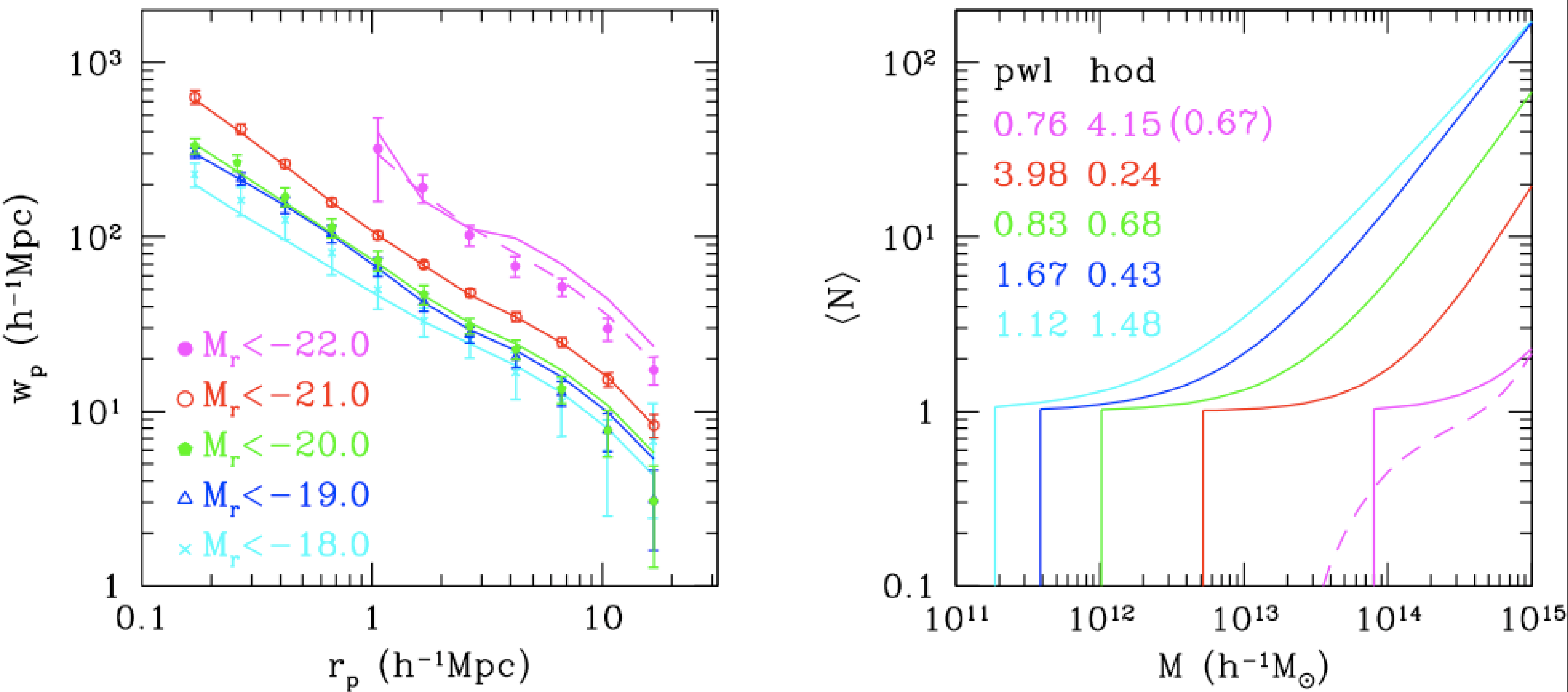
Zehavi et al, 2004

..and color



Zehavi et al, 2004

Where do these galaxies live?

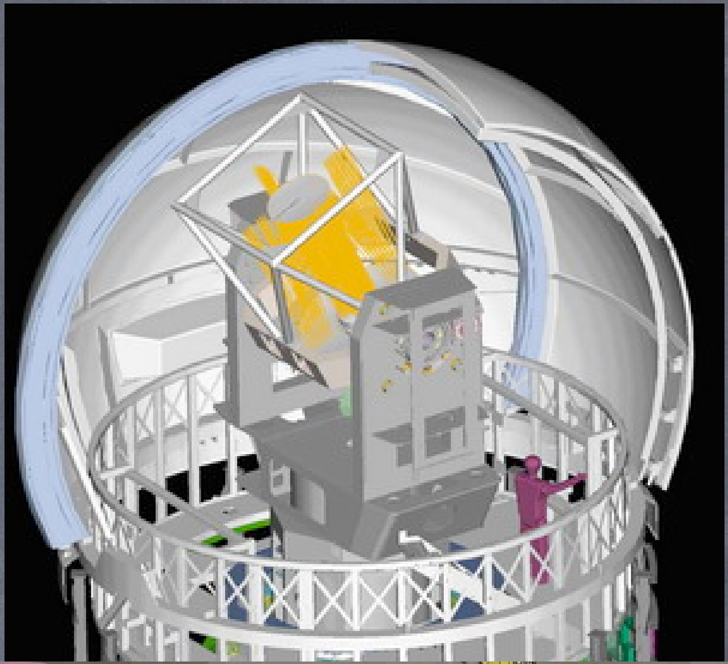


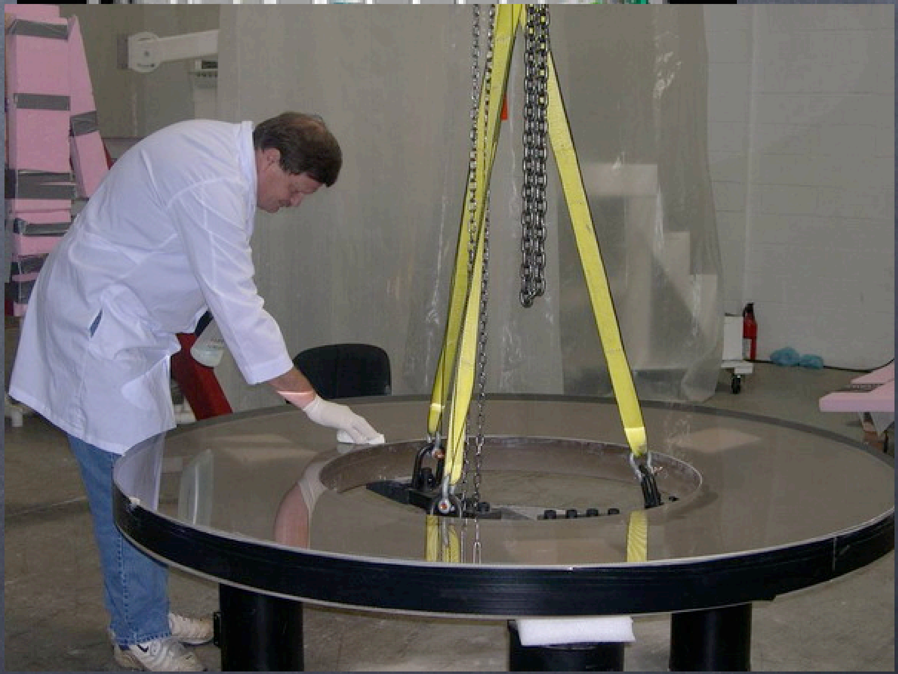
Zehavi et al, 2004

The Guide

- Theory / Modeling
    - P(k) Archaeology
    - The Connection to Galaxies - Large Scales
    - The Connection to Galaxies - Halo Models
- Surveys in Pictures
    - The SDSS in Pictures
- Imaging vs. Spectroscopy
    - Projected density fields
    - The SDSS as a proving ground - LRGs on large scales
    - LRGs on small scales
    - QSO-Galaxy cross correlations
    - Red galaxy merging in NDWFS

Imaging Surveys -- PanSTARRS

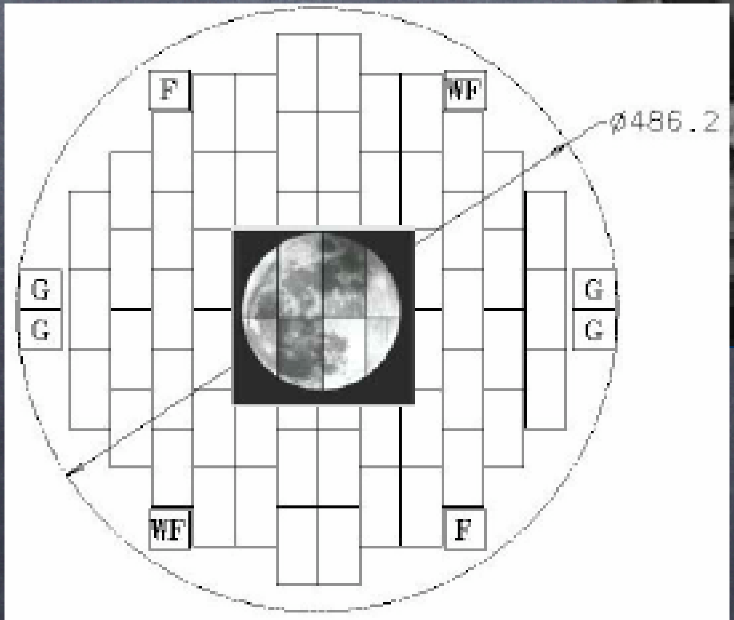




- 4x 1.8m telescopes, 3 deg. FOV
- Survey entire sky visible from Hawaii, mag. ~29.4
- Prototype : PS-1, being currently built, first light ~ 2007

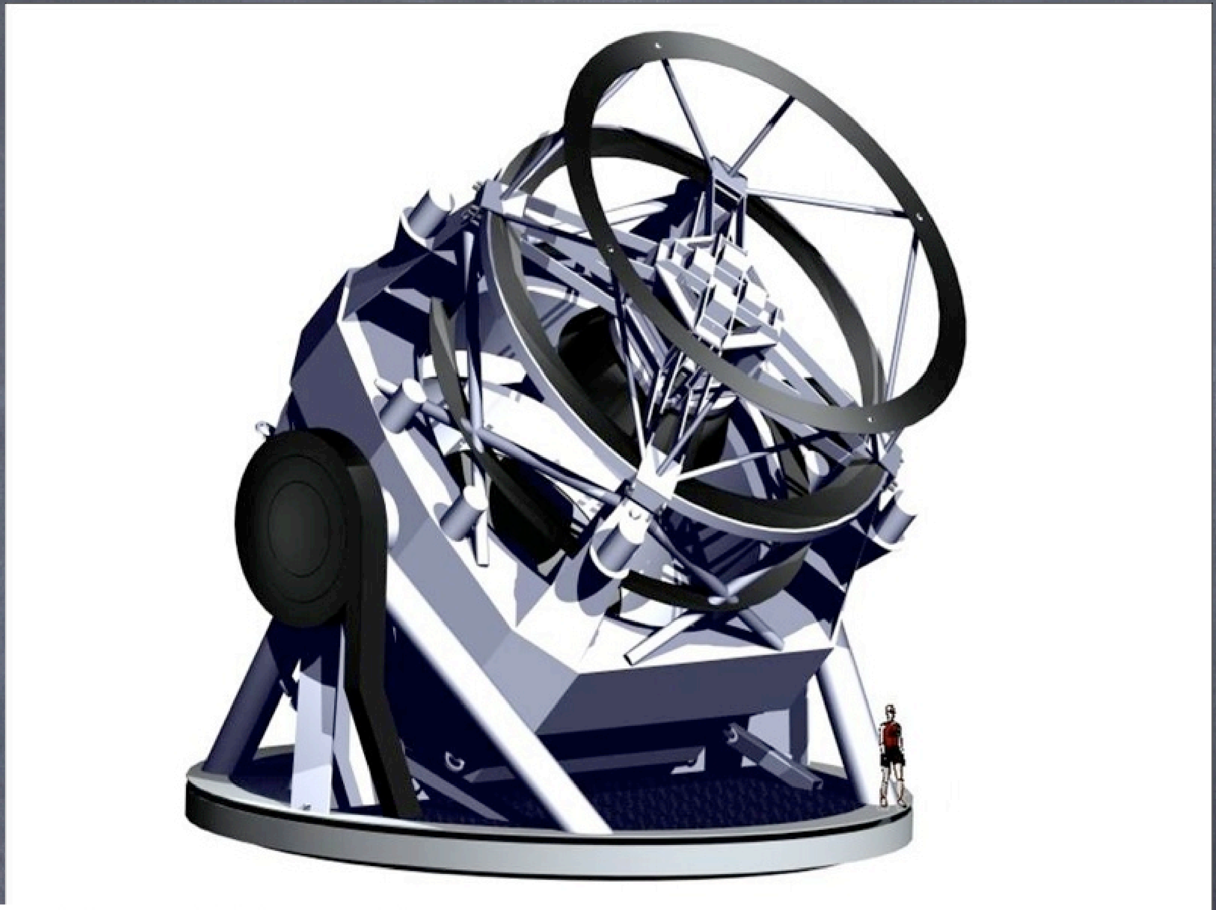
Imaging Surveys -- DES

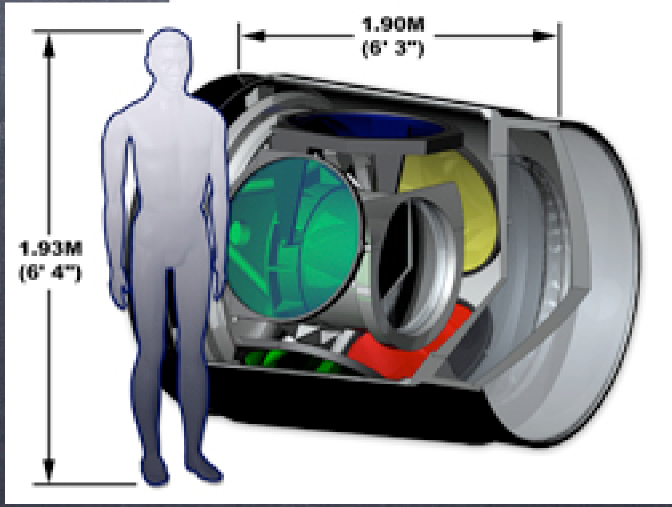
- 5000 sq.deg. field of southern Galactic cap
- Uses 4m Blanco telescope at CTIO
- 2.2 sq. deg. FOV



Imaging Surveys -- LSST

- 8.4m, 3.5 deg. FOV
- ugrizY filters
- Science goals : lensing, supernovae, time domain, solar system science





Why Photometry?

FASTER, WIDER, DEEPER

- ✓ Short integration times : cover large areas faster
- ✓ Wider and deeper : lower cosmic variance
- ✓ Wider and deeper : larger scales
- ✓ Deeper : Fainter population of galaxies
- ✓ High z : less nonlinearity
- ? Projection onto 2D : loss of radial modes
  - ✓ Mitigated with photometric redshifts
  - ✓ Mitigated with cross correlations
  - ✓ Avoids complications of redshift-space distortions

Projected density fields

- Project to 2D in redshift slice :

$$\delta_g(\hat{n}) = \int dy\, y^2 \phi(y) \delta_g(y, y\hat{n})$$

- Angular power spectrum simply windowed version of 3D P(k) :

$$C_l^{gg} = 4\pi \int dk\, \frac{\Delta^2(k)}{k}\, |W(k)|^2$$

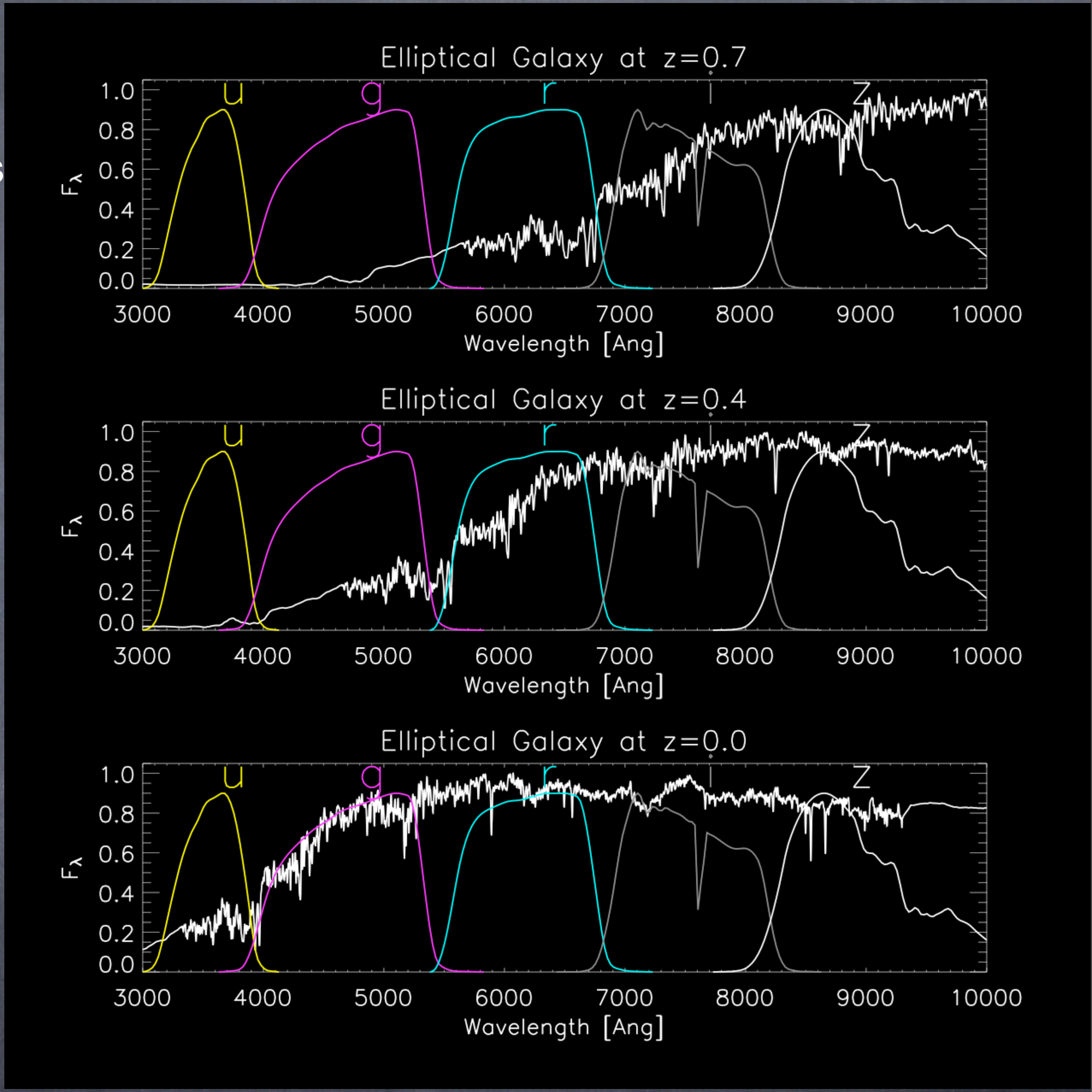
- Window function :

$$W_l(k) = \int dy\, \phi(y) D(y) j_l(ky)$$

- For large l, collapse to l/k

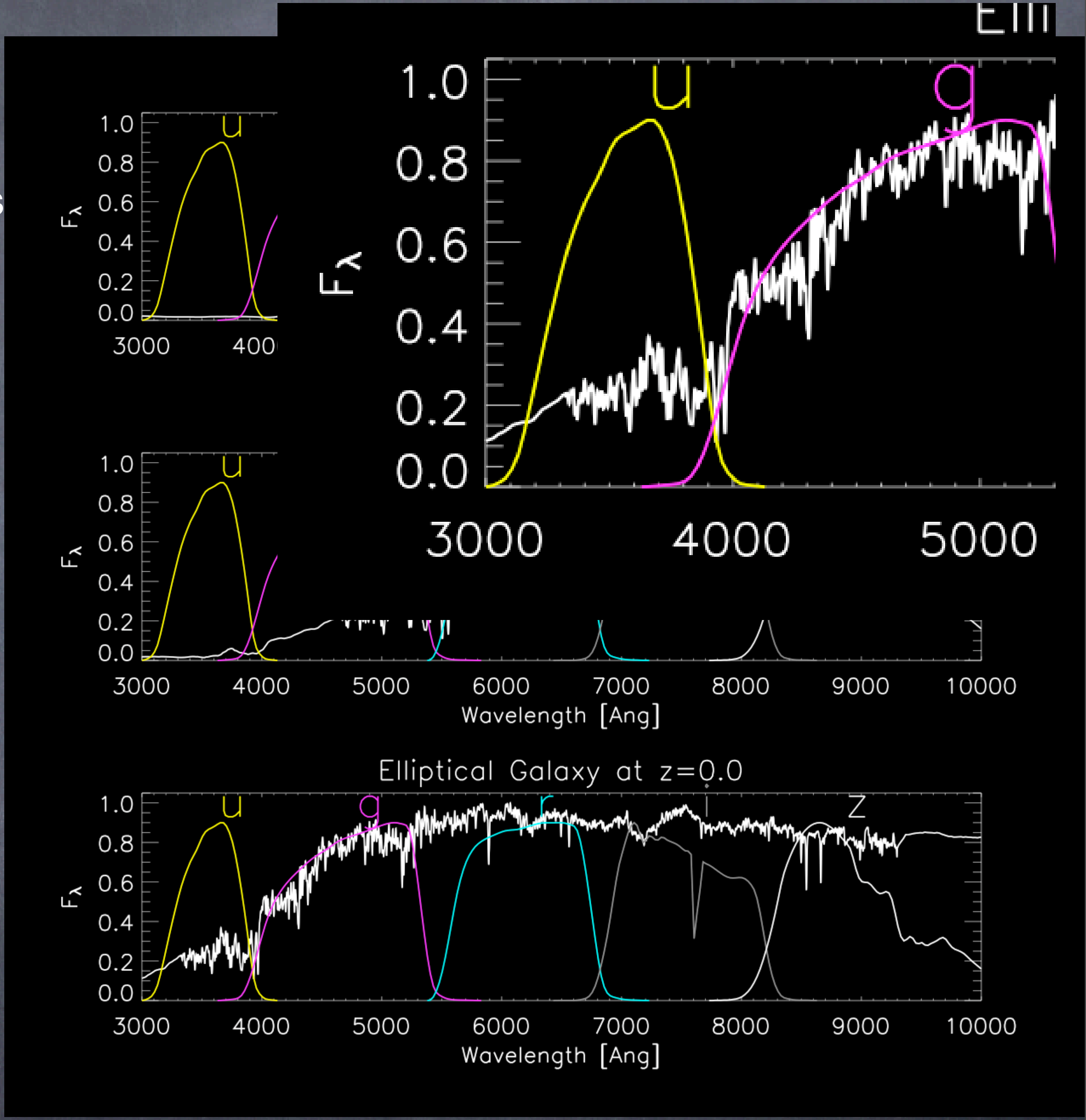
Luminous Red Galaxies

- Probe large cosmological volumes
    - Need luminous probes (LRGs)
- Good photometric redshifts
    - Old elliptical systems
    - Uniform spectral energy distributions (LRGs), strong 4000 Angstrom break
    - Multi-band photometry (SDSS)
- Ease of selection
    - Uniform SEDs imply uniform colors, tight color locus



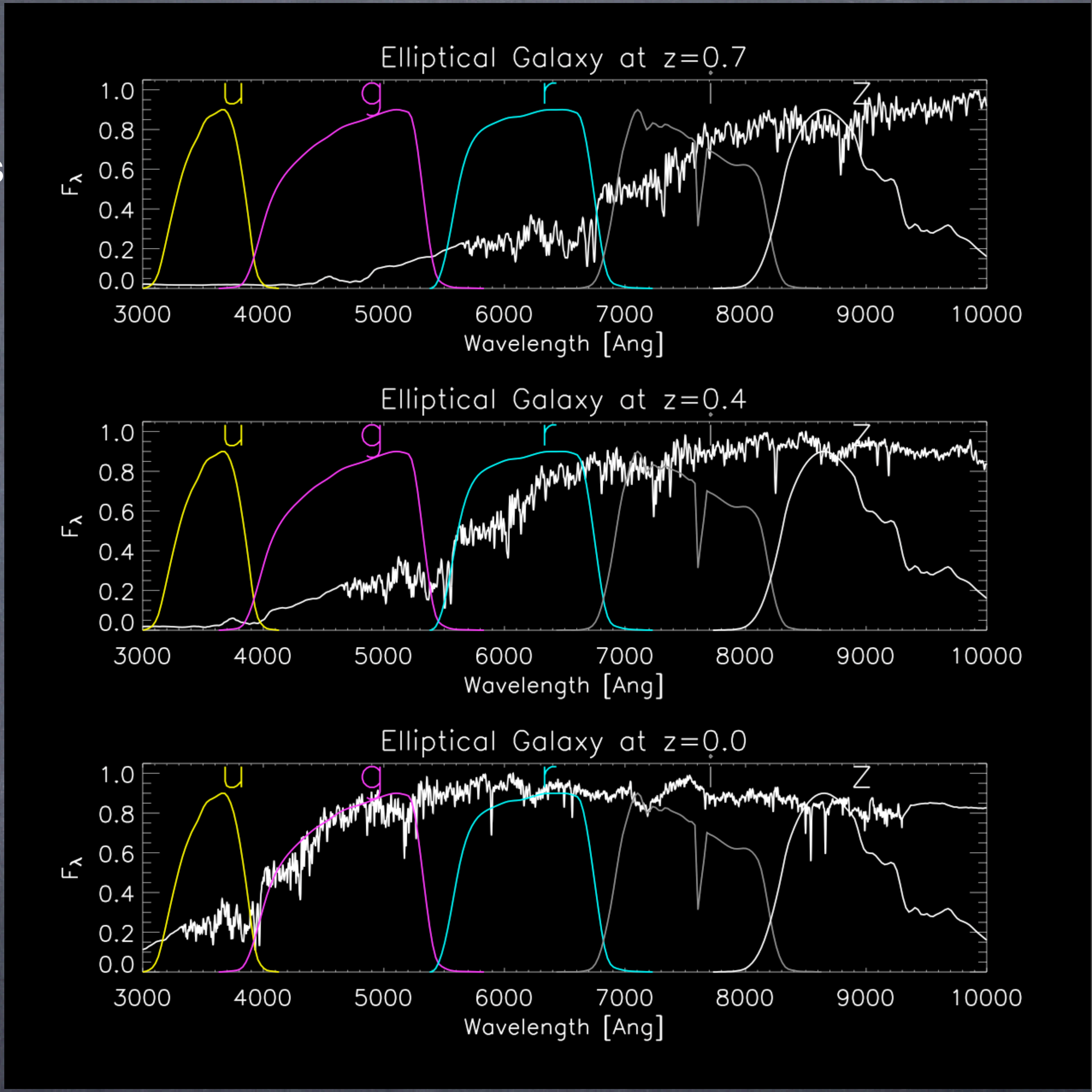
Luminous Red Galaxies

- Probe large cosmological volumes
  - Need luminous probes (LRGs)
- Good photometric redshifts
  - Old elliptical systems
  - Uniform spectral energy distributions (LRGs), strong 4000 Angstrom break
  - Multi-band photometry (SDSS)
- Ease of selection
  - Uniform SEDs imply uniform colors, tight color locus



Luminous Red Galaxies

- Probe large cosmological volumes
    - Need luminous probes (LRGs)
- Good photometric redshifts
    - Old elliptical systems
    - Uniform spectral energy distributions (LRGs), strong 4000 Angstrom break
    - Multi-band photometry (SDSS)
- Ease of selection
    - Uniform SEDs imply uniform colors, tight color locus

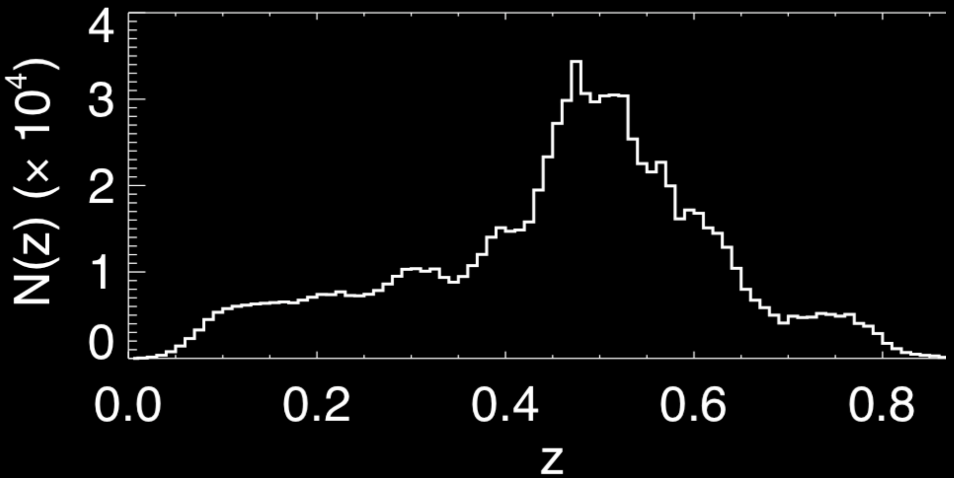


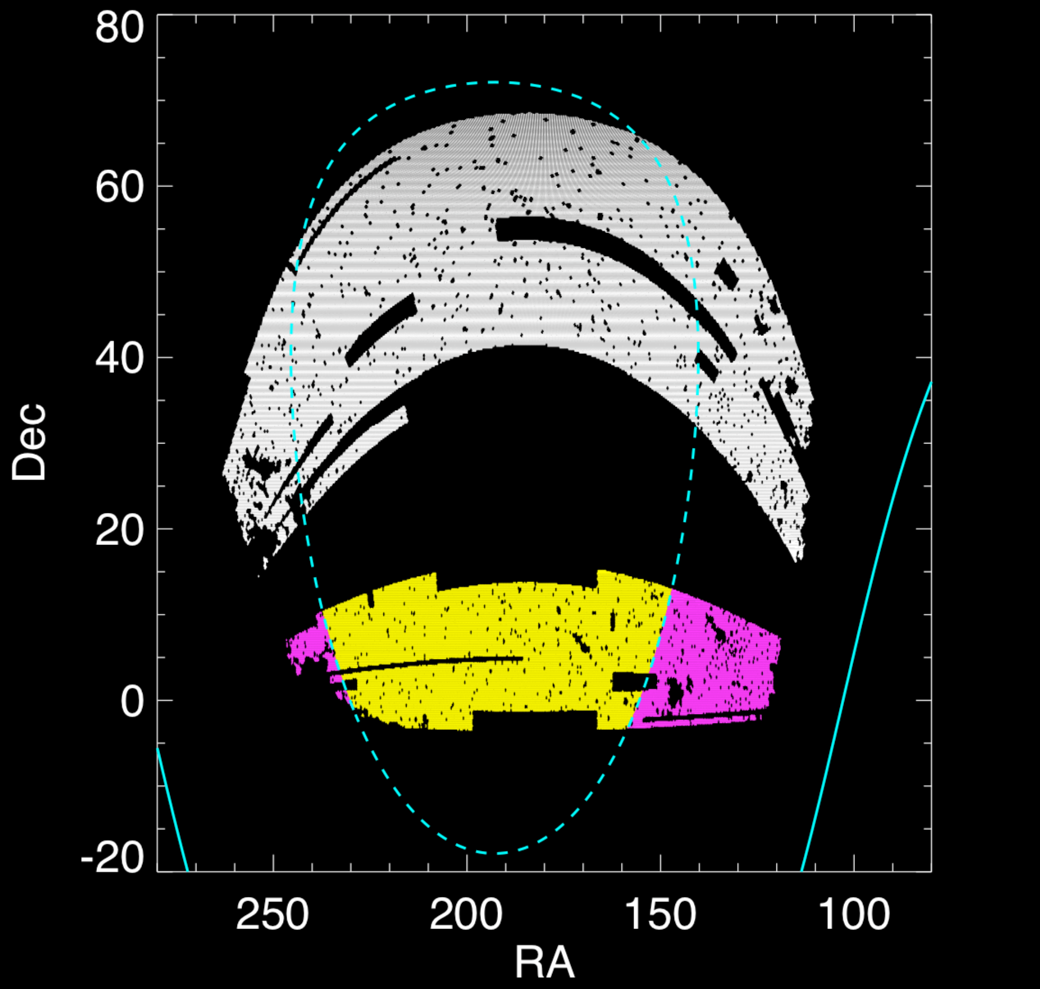
The Sample

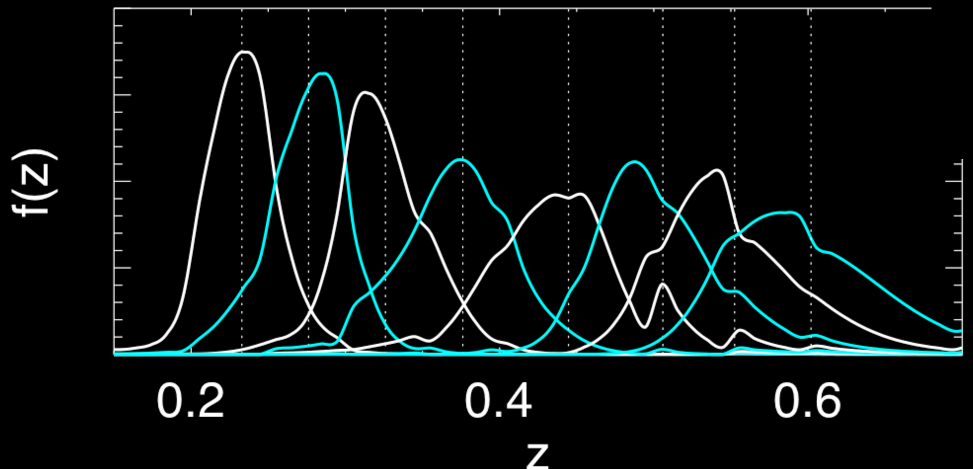
3,528 sq. deg (2,384+1,144)

Complete from z ~ 0.2 to 0.6

8 photo-z slices with dz = 0.05



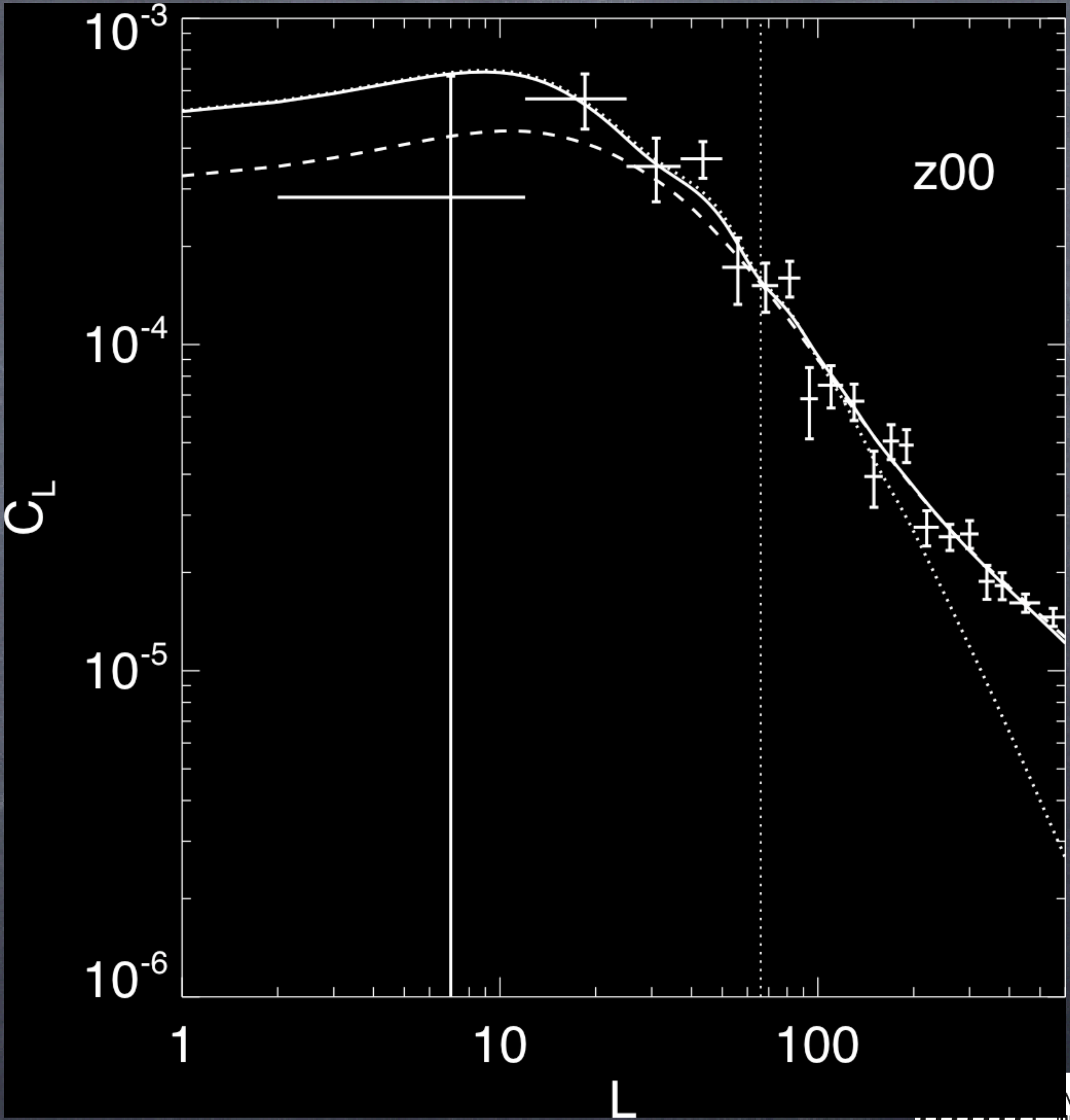




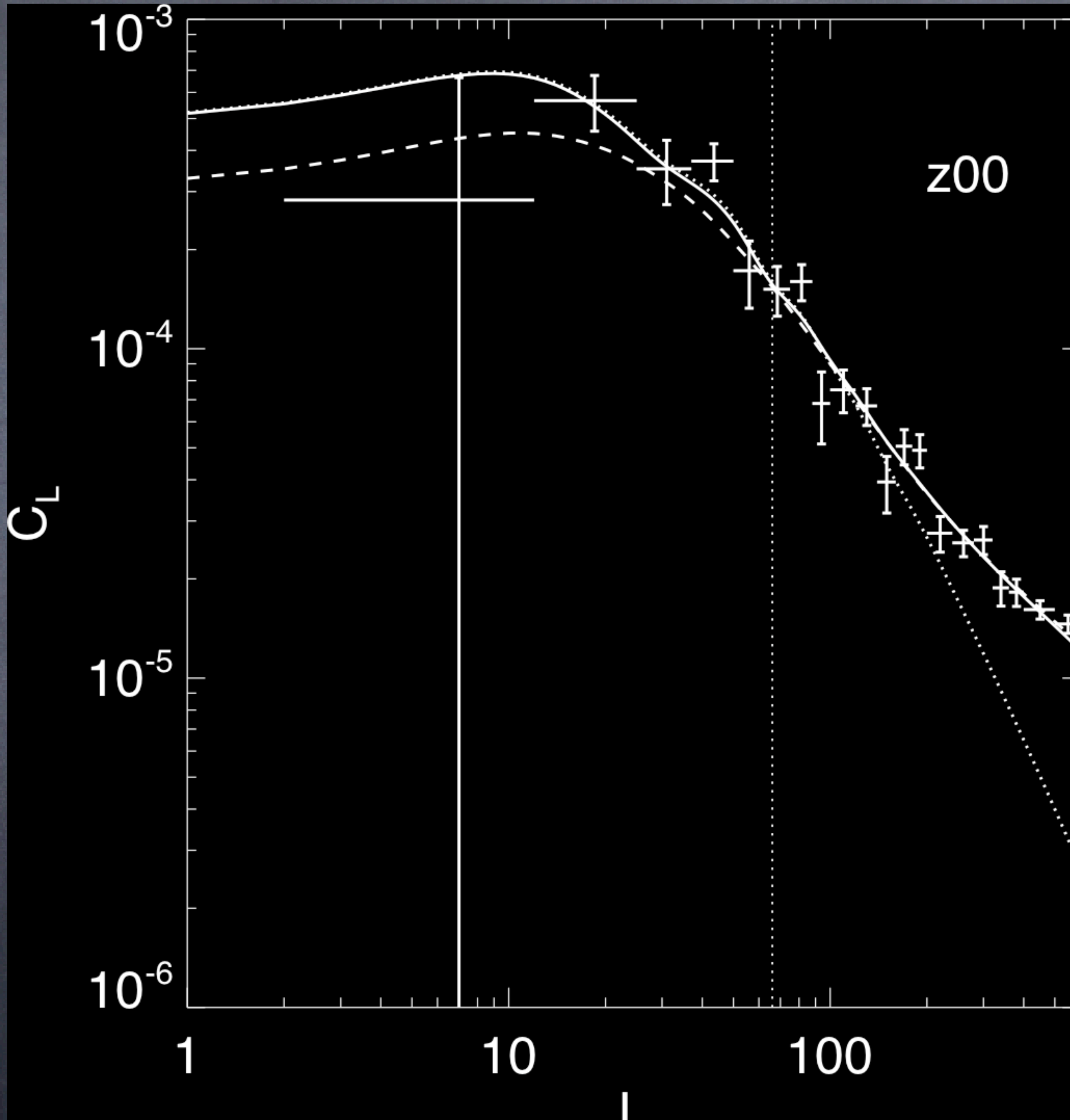
1.5 (Gpc/h)^3

The Angular Power Spectrum

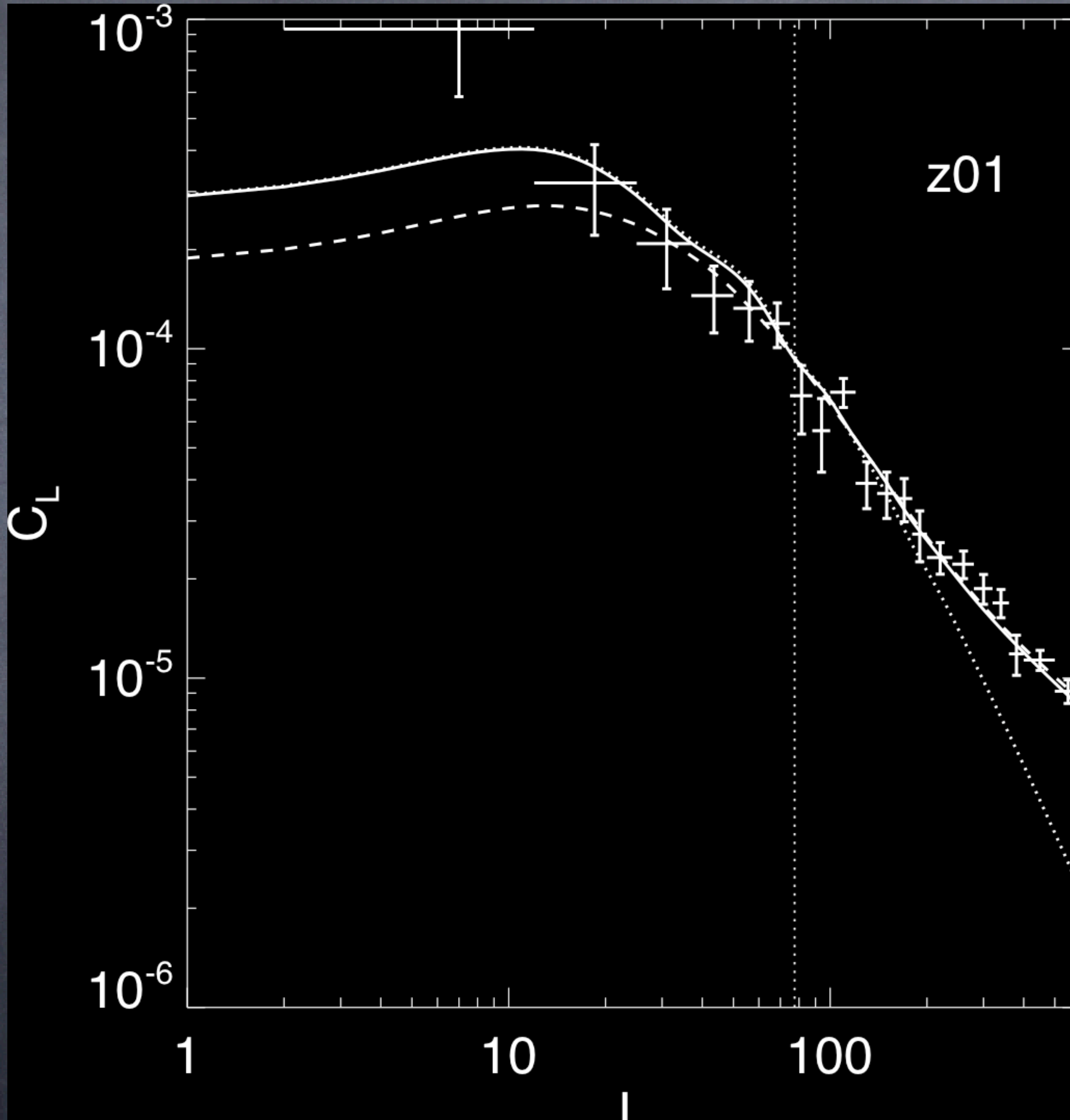
- Evolution of amplitude
- Evolution of shape
    - Break moves to smaller scales as redshift increases



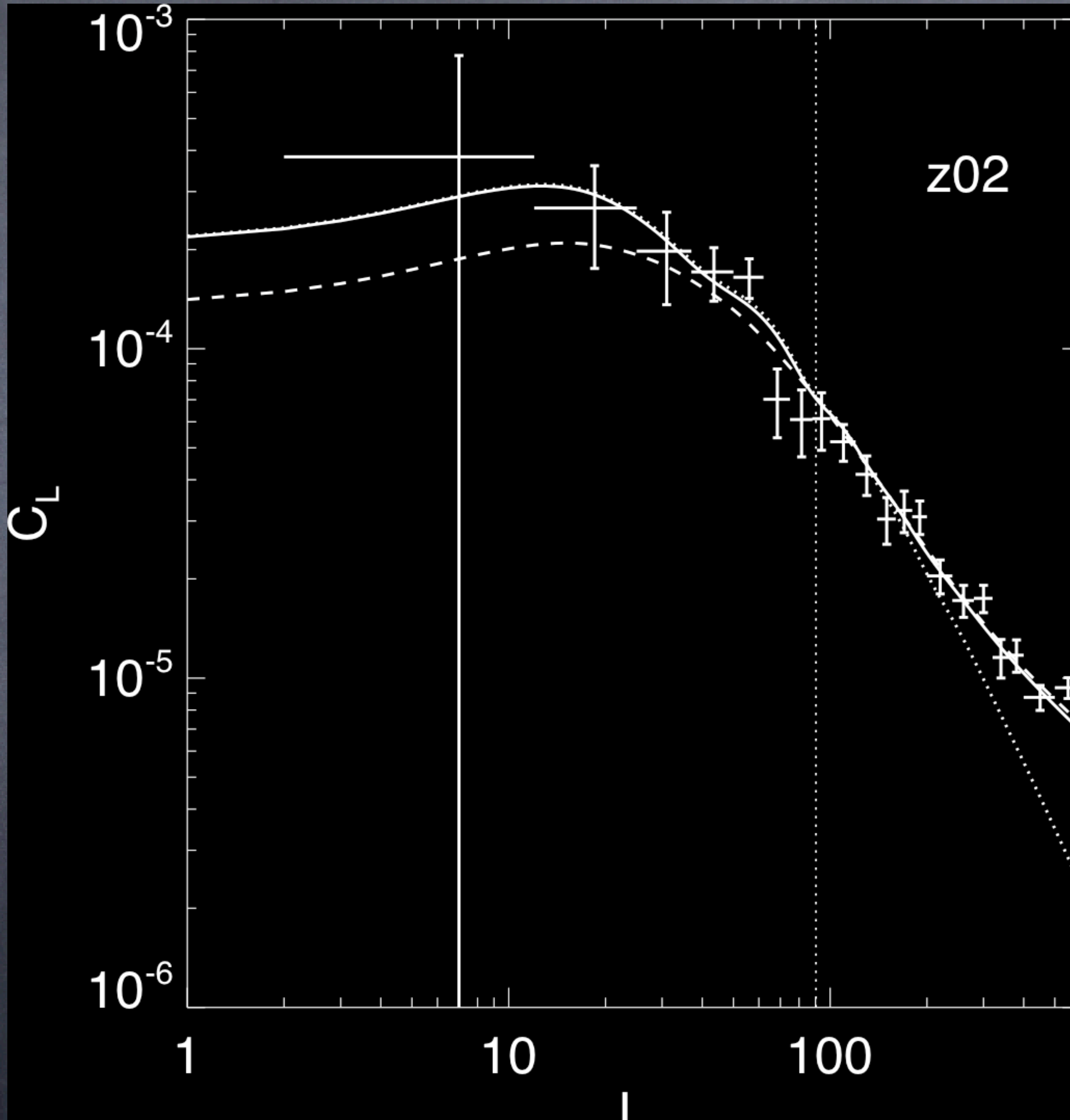
The Angular Power Spectrum



The Angular Power Spectrum

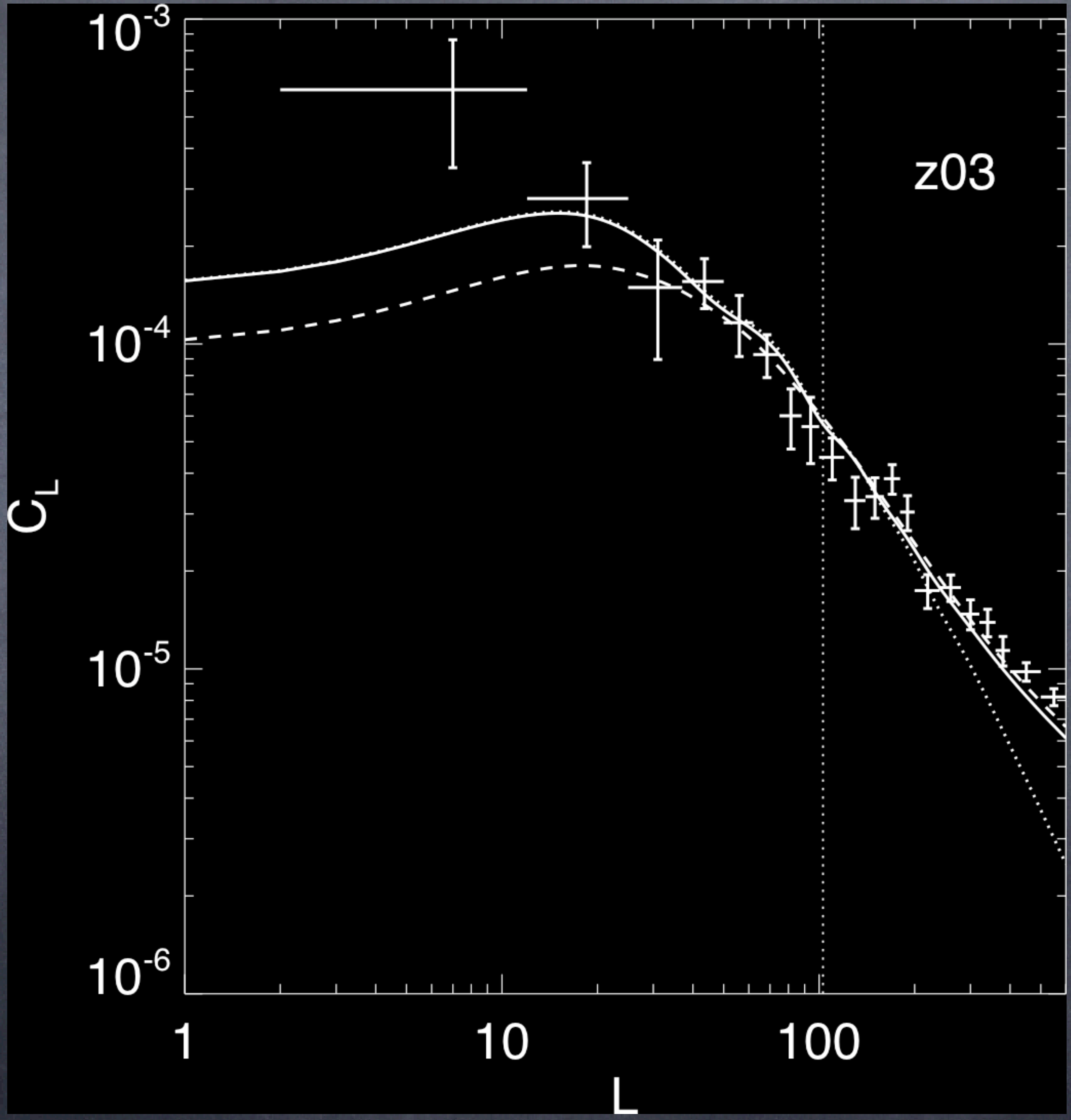


The Angular Power Spectrum

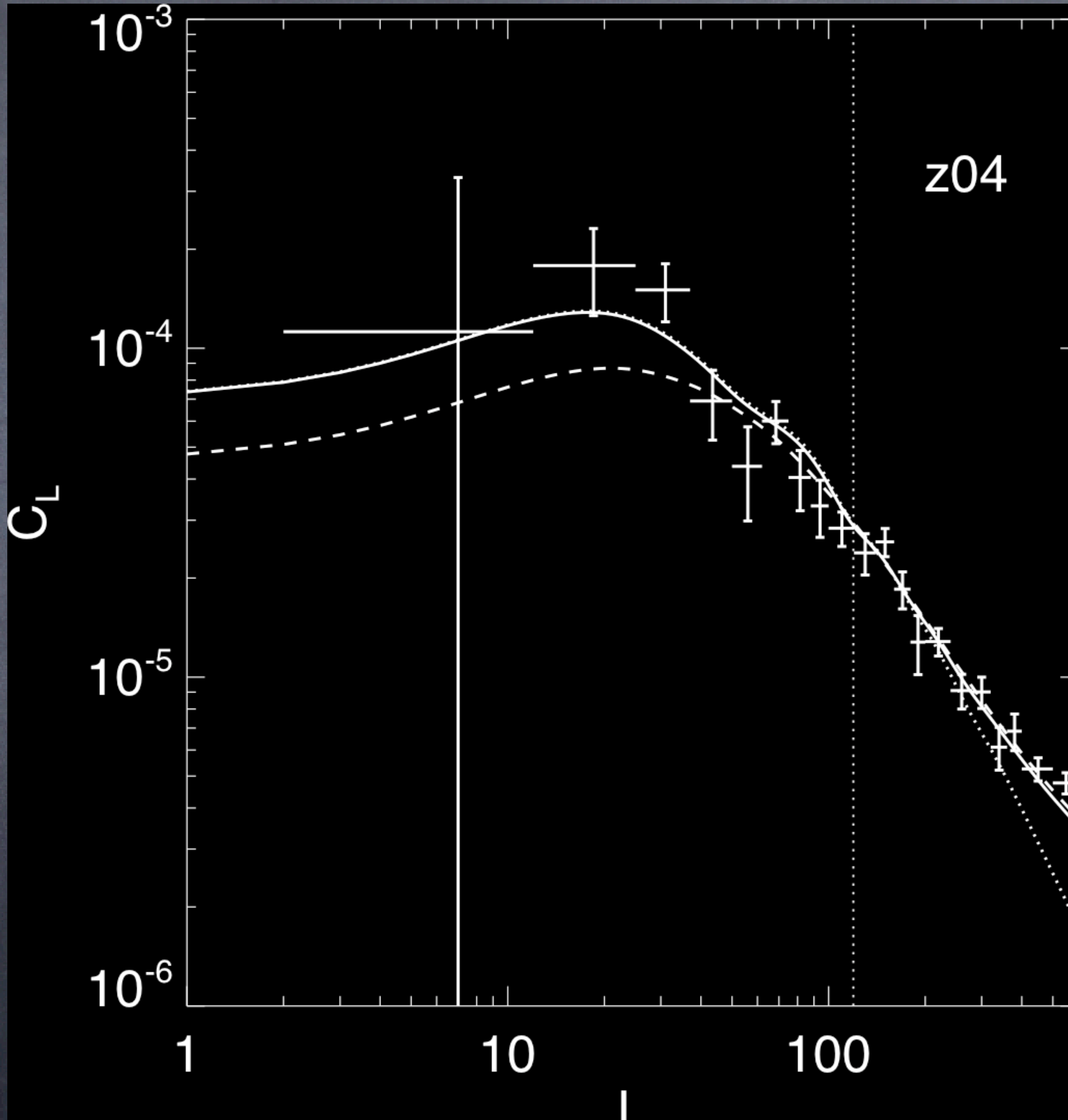


Nikhil Padmanabhan

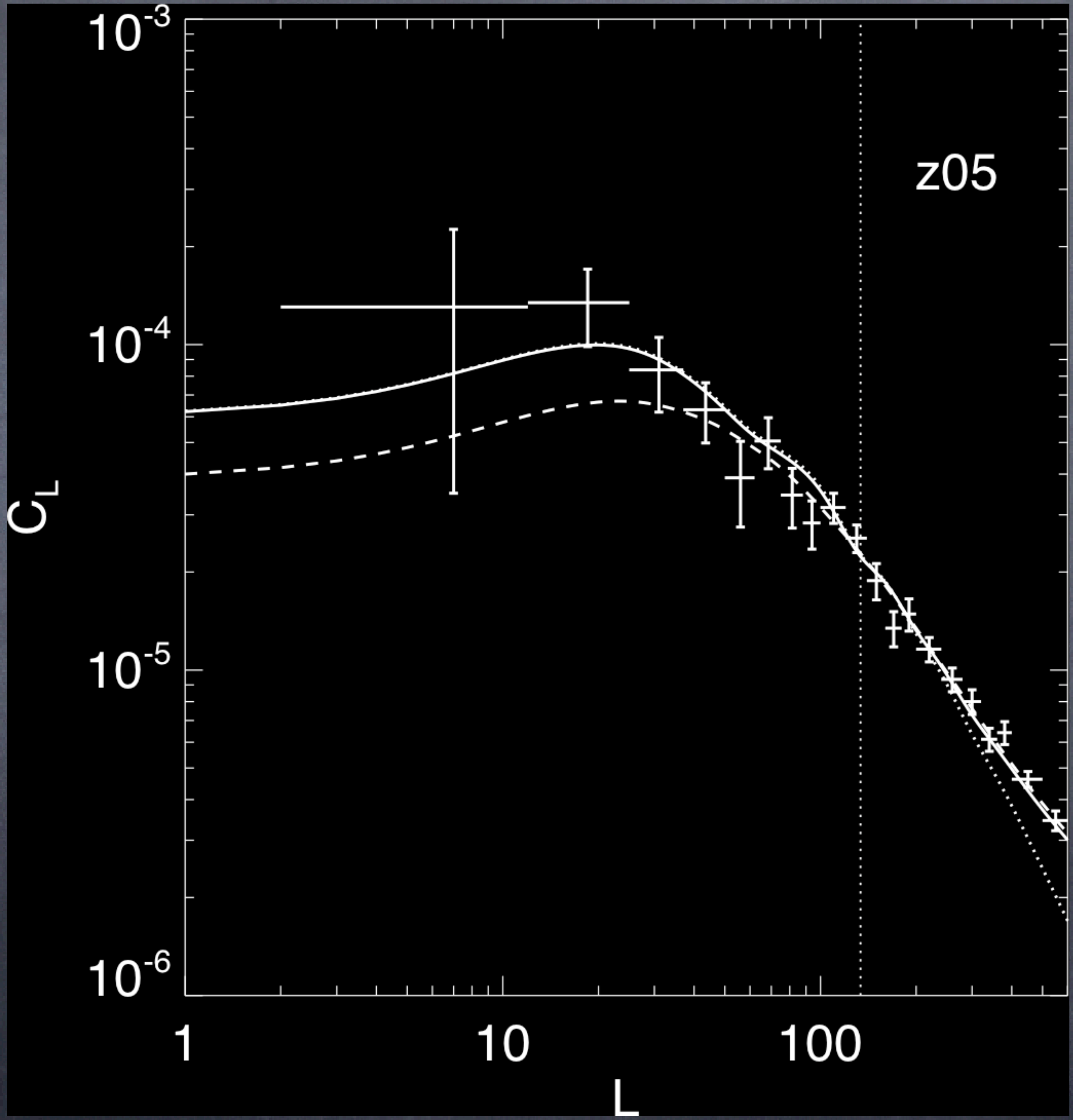
The Angular Power Spectrum



The Angular Power Spectrum

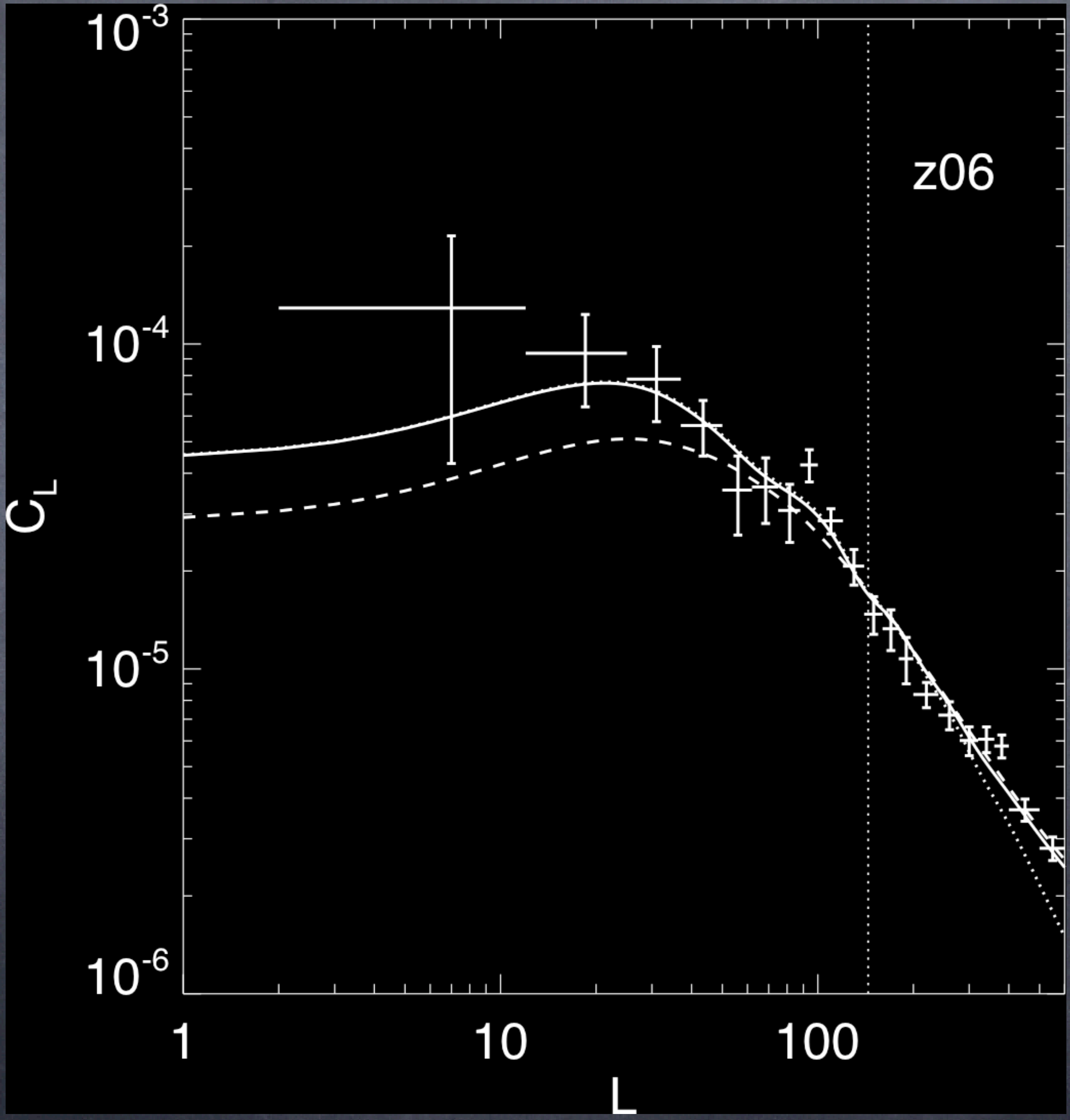


The Angular Power Spectrum

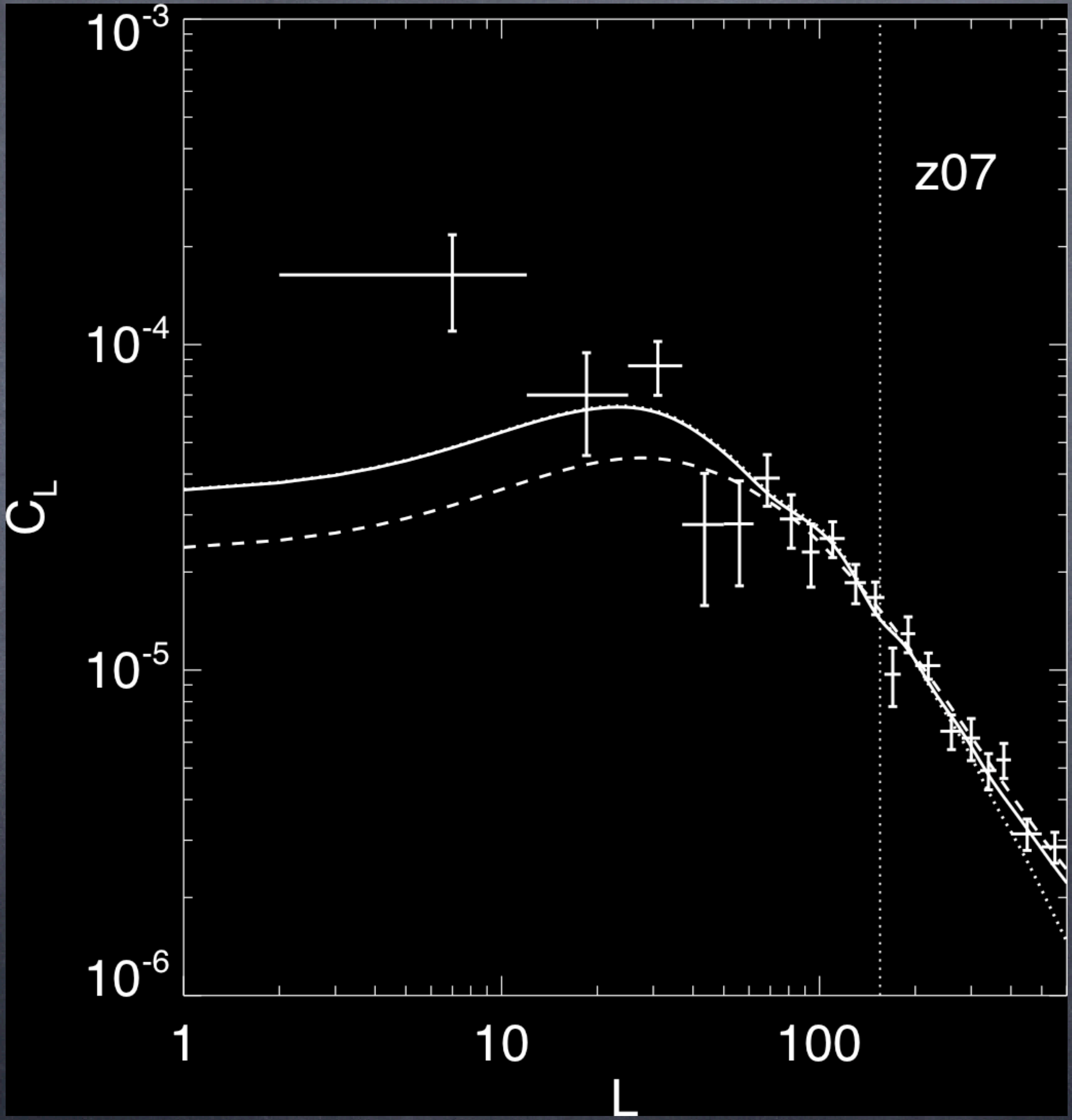


Nikhil Padmanabhan

The Angular Power Spectrum



The Angular Power Spectrum

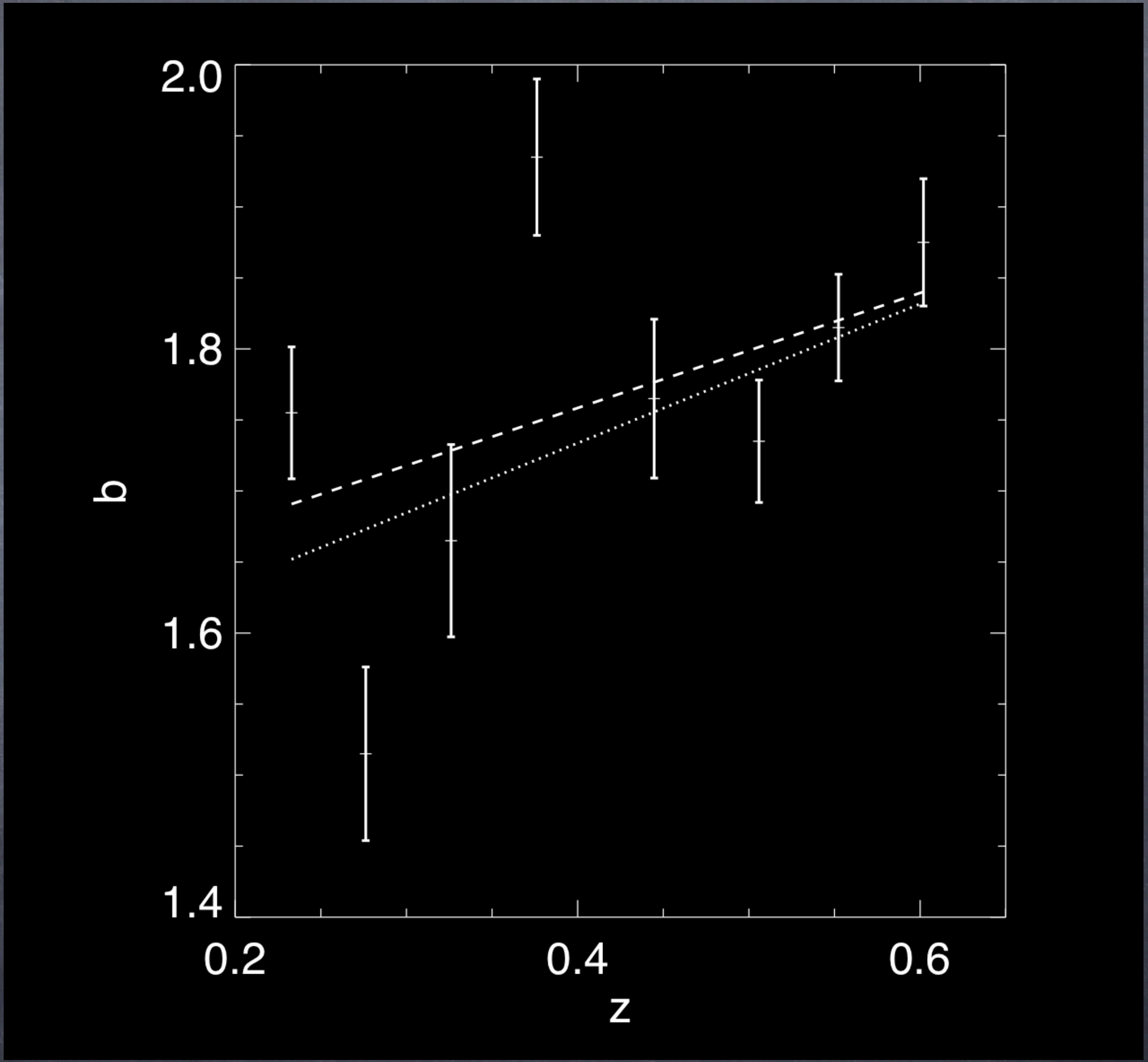


Bias

LRGs luminous, highly biased

Slight population variations change the bias

Increasing bias with increasing z



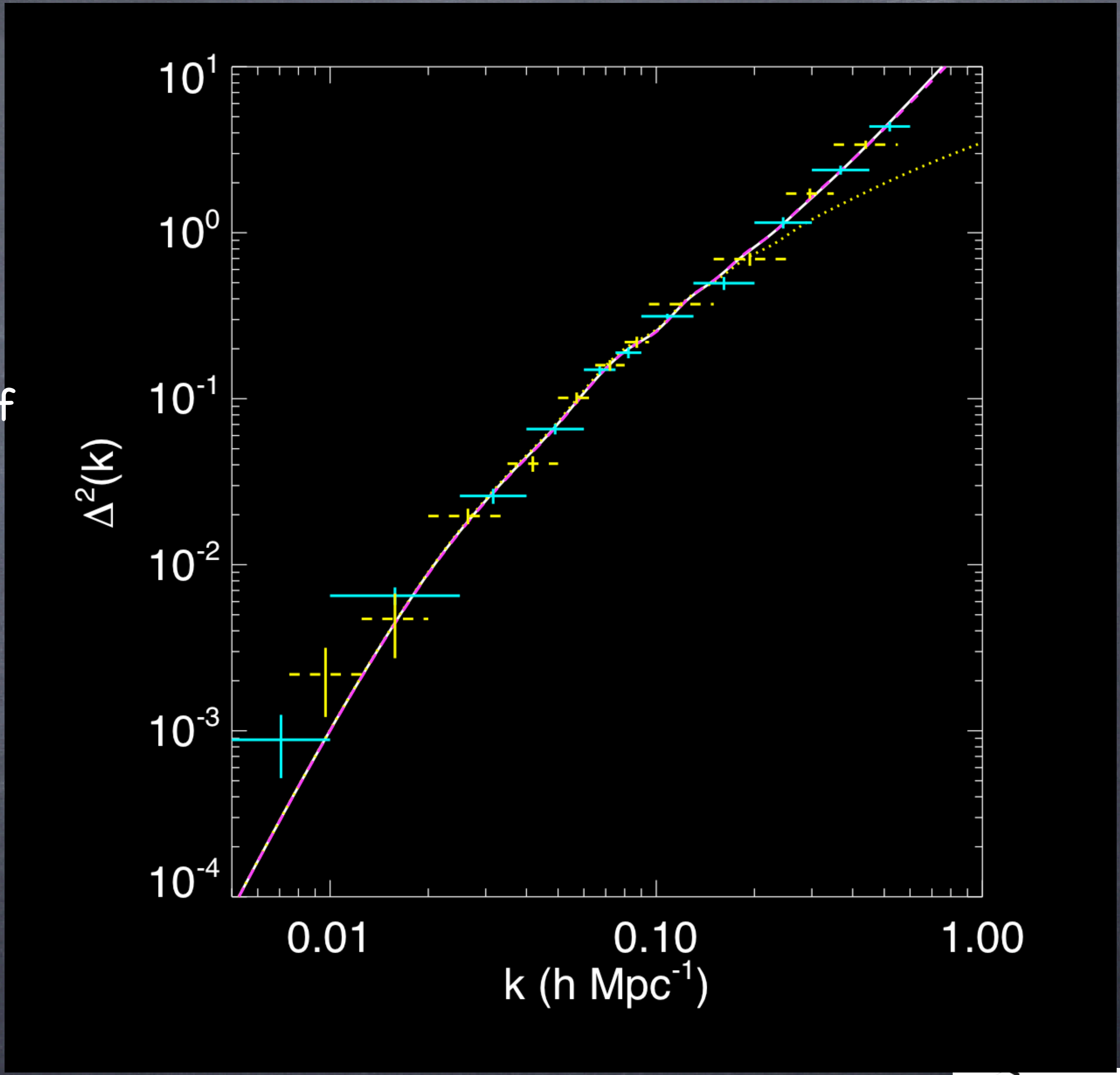
The 3D Power Spectrum

2D power spectrum contains all the information, but 3D power spectrum allows for model independent studies

2D spectrum is a convolution of 3D P(k), need binning

Stack linear power spectra correcting for bias

Two binnings not independent, bins anticorrelated



3D power spectrum using photo-z

Large Scales

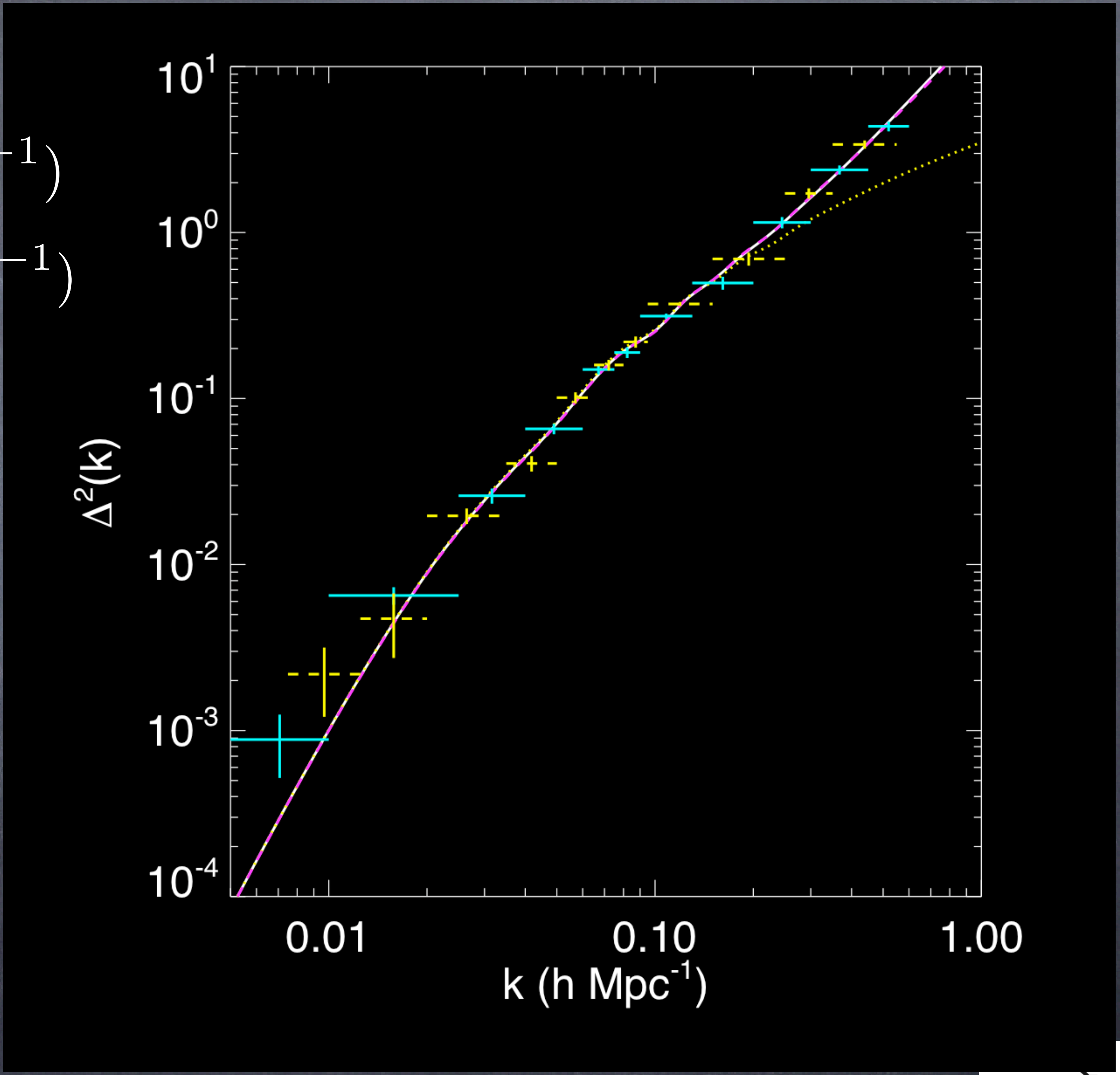
Large scales:

$$2\sigma(k < 0.01 h\mathrm{Mpc}^{-1})$$

$$5.5\sigma(k < 0.02 h\mathrm{Mpc}^{-1})$$

Small scales:
Lack of redshift space distortions!

Real space P(k)



Detection of clustering on large scales

Large Scales

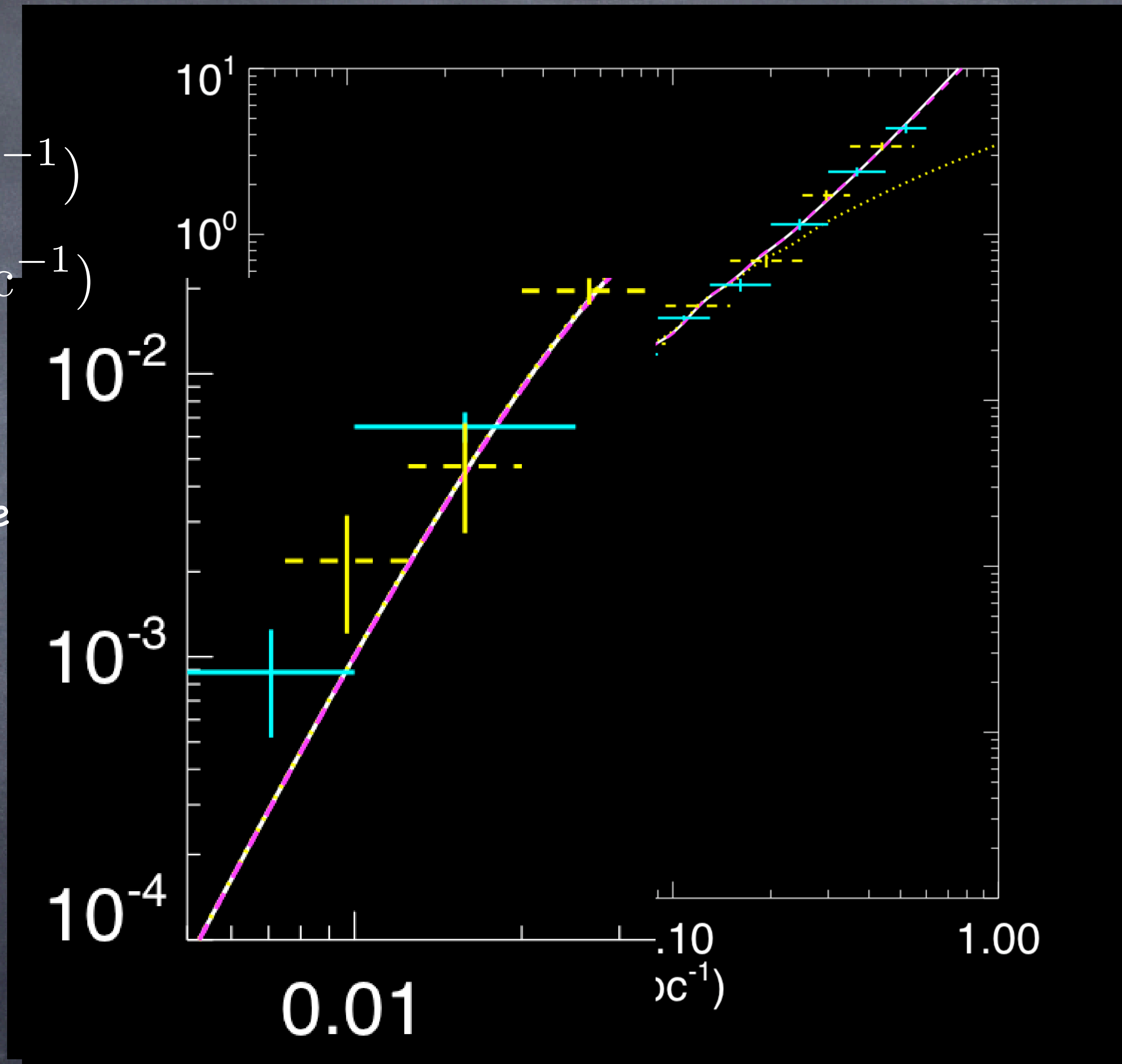
Large scales:

$$2\sigma(k < 0.01h\mathrm{Mpc}^{-1})$$

$$5.5\sigma(k < 0.02h\mathrm{Mpc}^{-1})$$

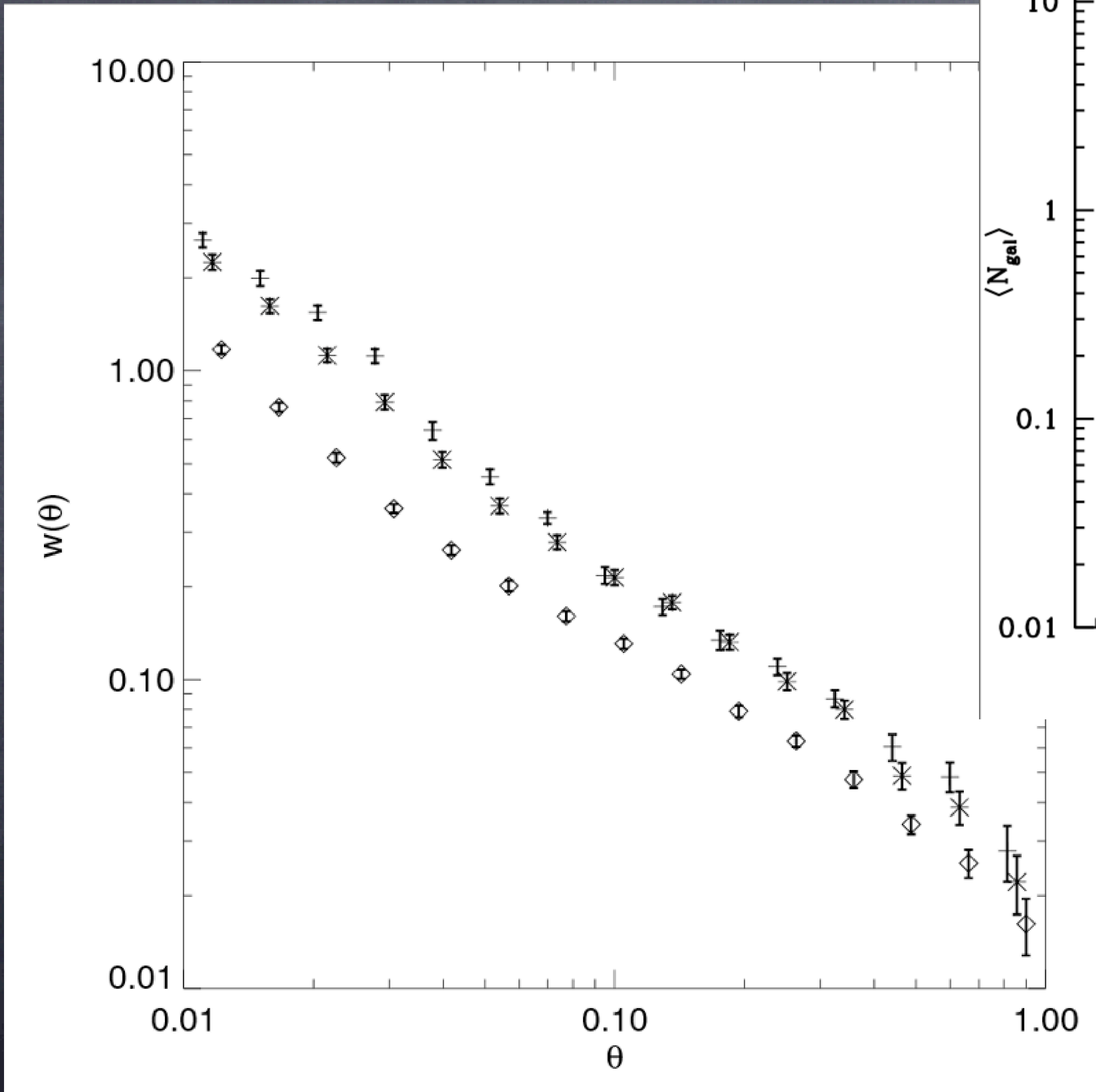
Small scales:
Lack of redshift space distortions!

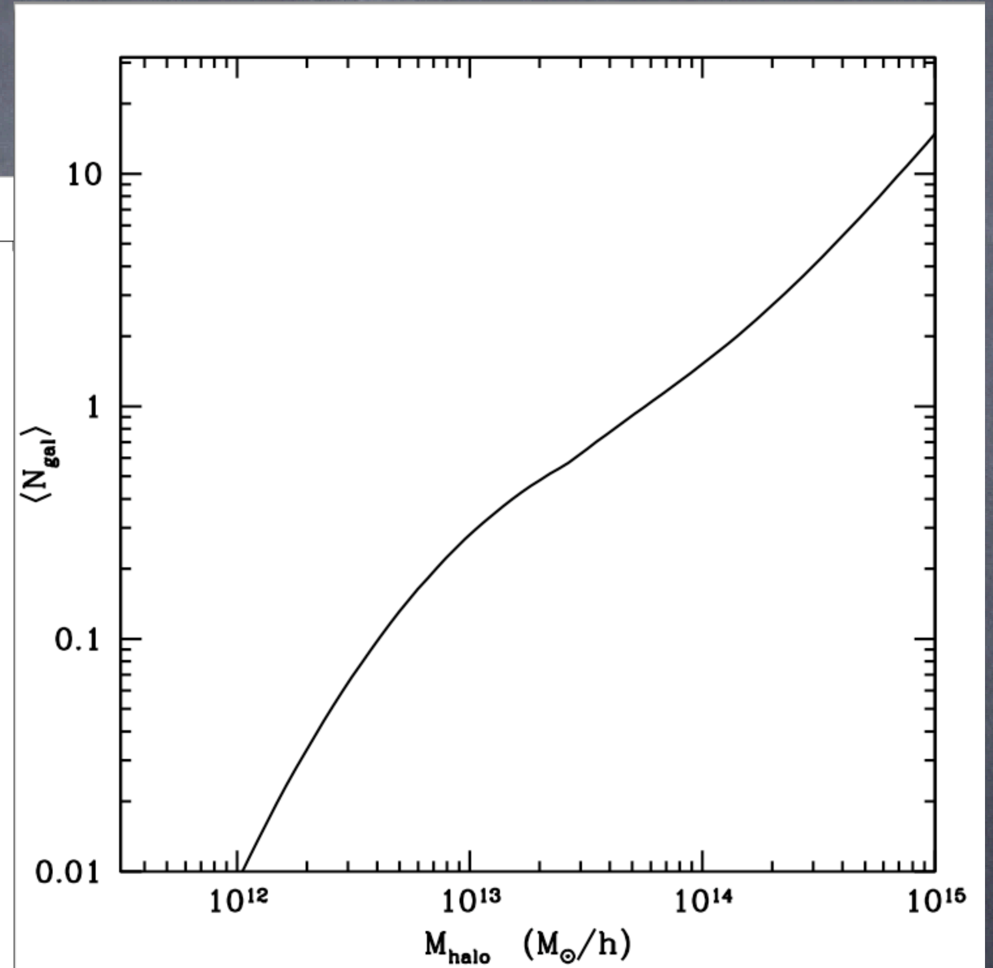
Real space P(k)



Detection of clustering on large scales

LRG Clustering on small scales



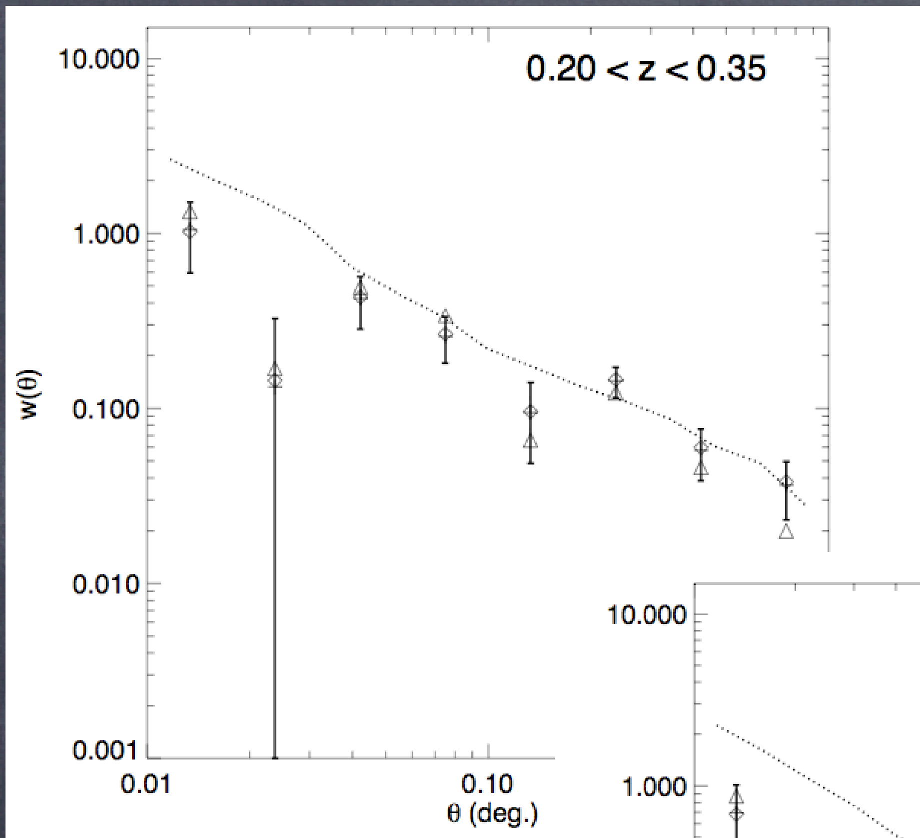


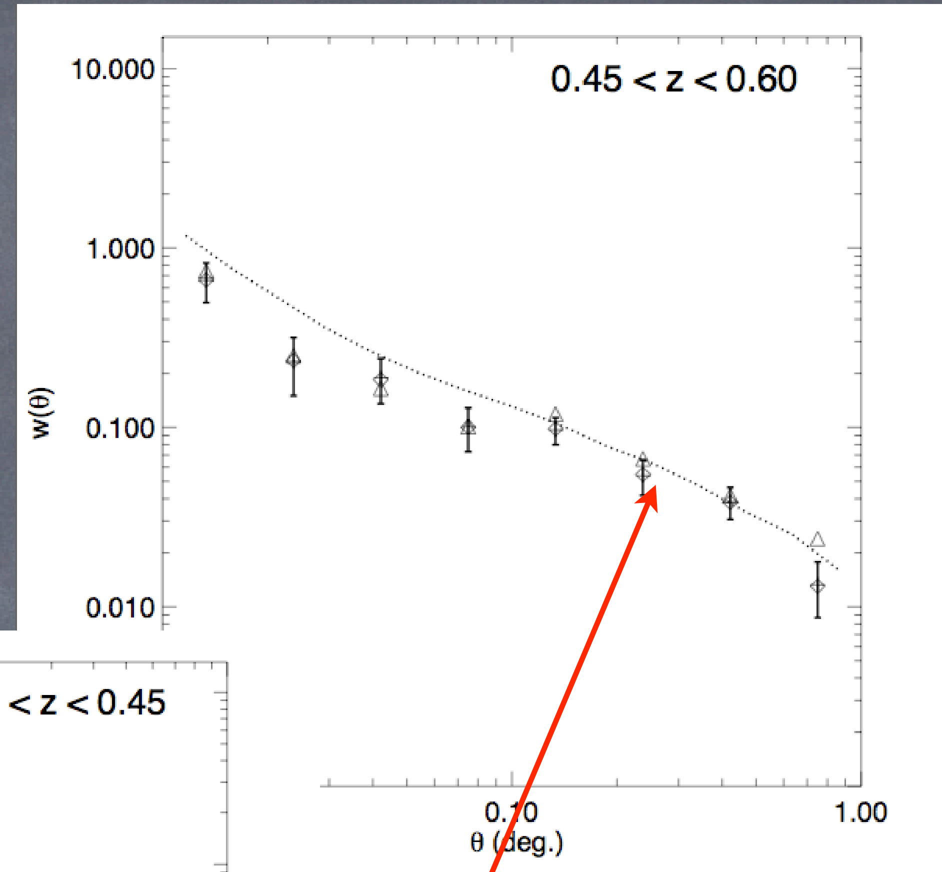
NP, White, Norberg, Porciani, in prep

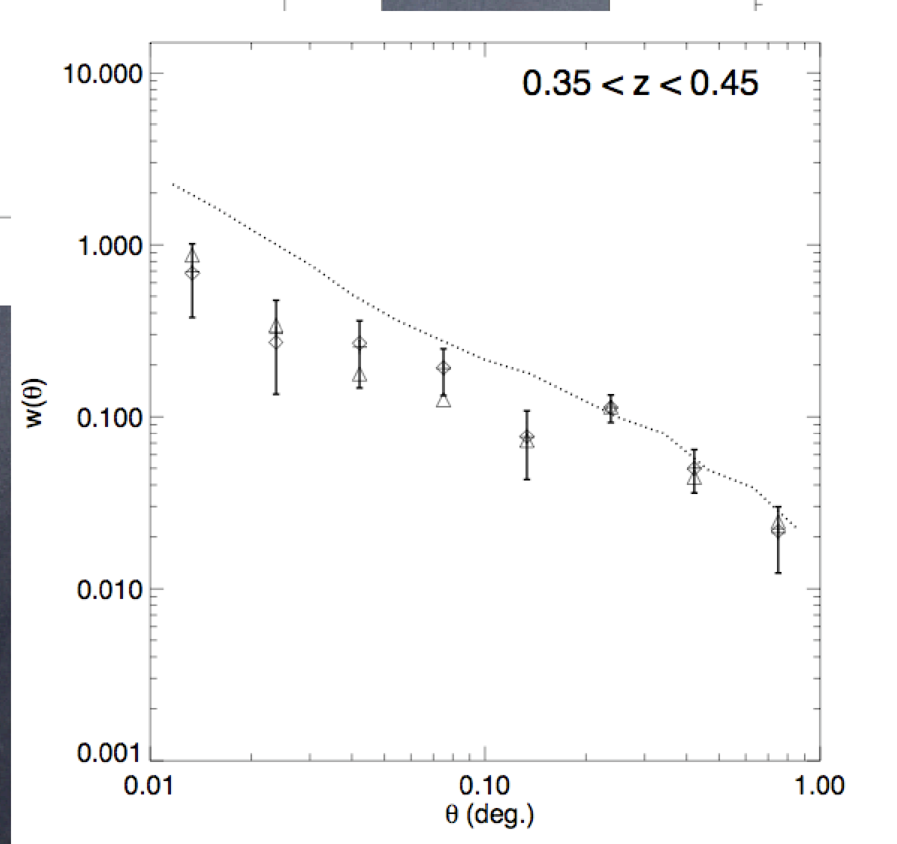
Cross-correlations

- On small scales, signal dominated by intrinsic galaxy correlations, not projection effects
- Use a tracer population with well measured redshifts to localize a broad redshift distribution.
- Eg. work by Eisenstein et al & Masjedi et al on the environments of LRGs, Coil et al on DEEP2-QSO cross correlations, Adelberger & Steidel on high-z galaxy-QSO cross correlations.
- SDSS QSO-Galaxy cross-correlations at low-z
  - QSO shot noise too large to measure auto-correlation
  - Cross correlate with photometric LRGs - push to higher redshift and higher number density than possible with spectroscopic galaxies

QSO- Galaxy correlations







Large scale bias same as LRGs!!

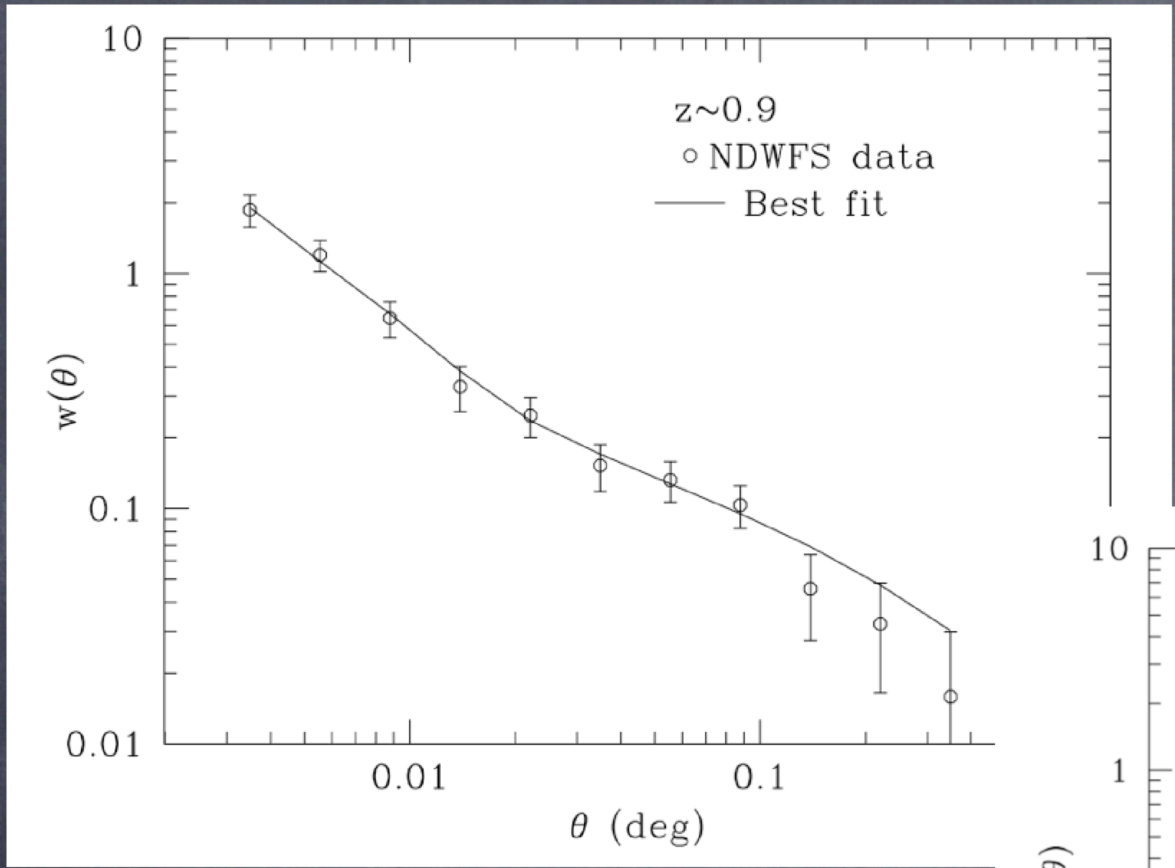
NP, White, Norberg, Porciani, in prep

NDWFS

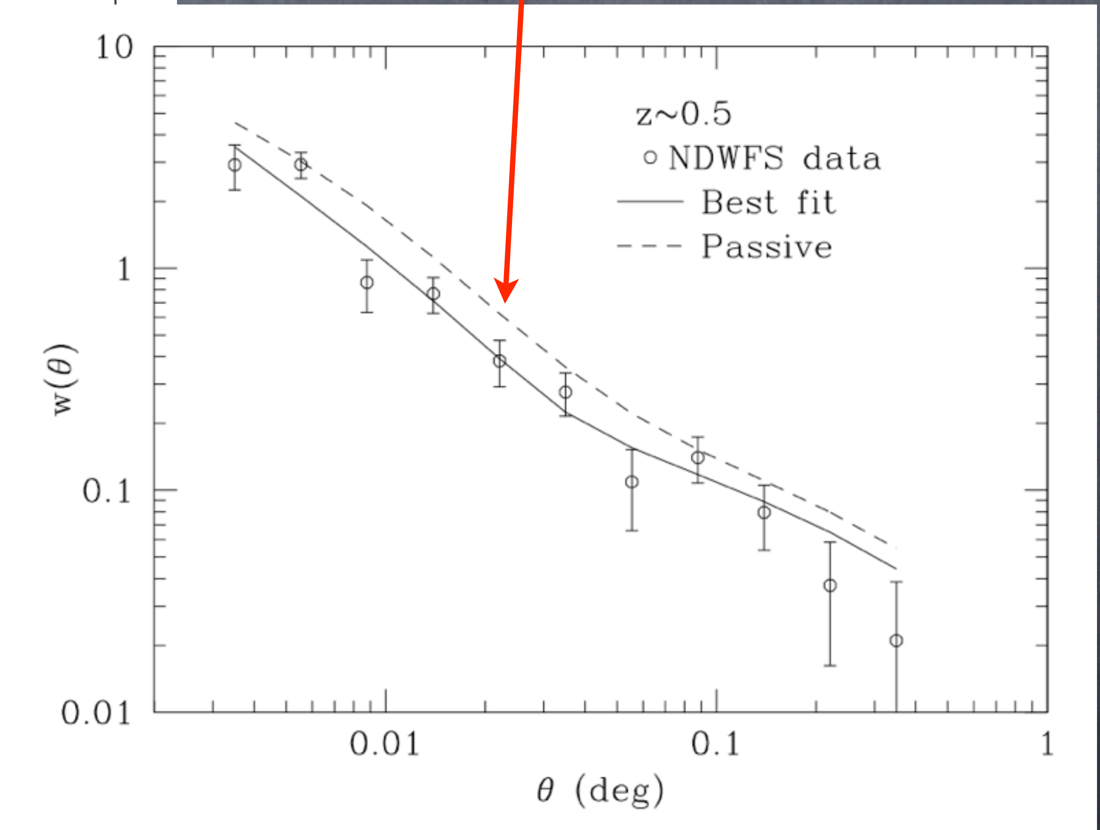
- 6-band (B,R,I,J,H,K) imaging of two 9 sq. deg. fields
- Spitzer follow-up observations (IRAC shallow survey)
- Limiting magnitude R ~26
- Max. z ~ 1.5-2

http://www.noao.edu/noao/noaodeep/index.html

Red Galaxy Evolution



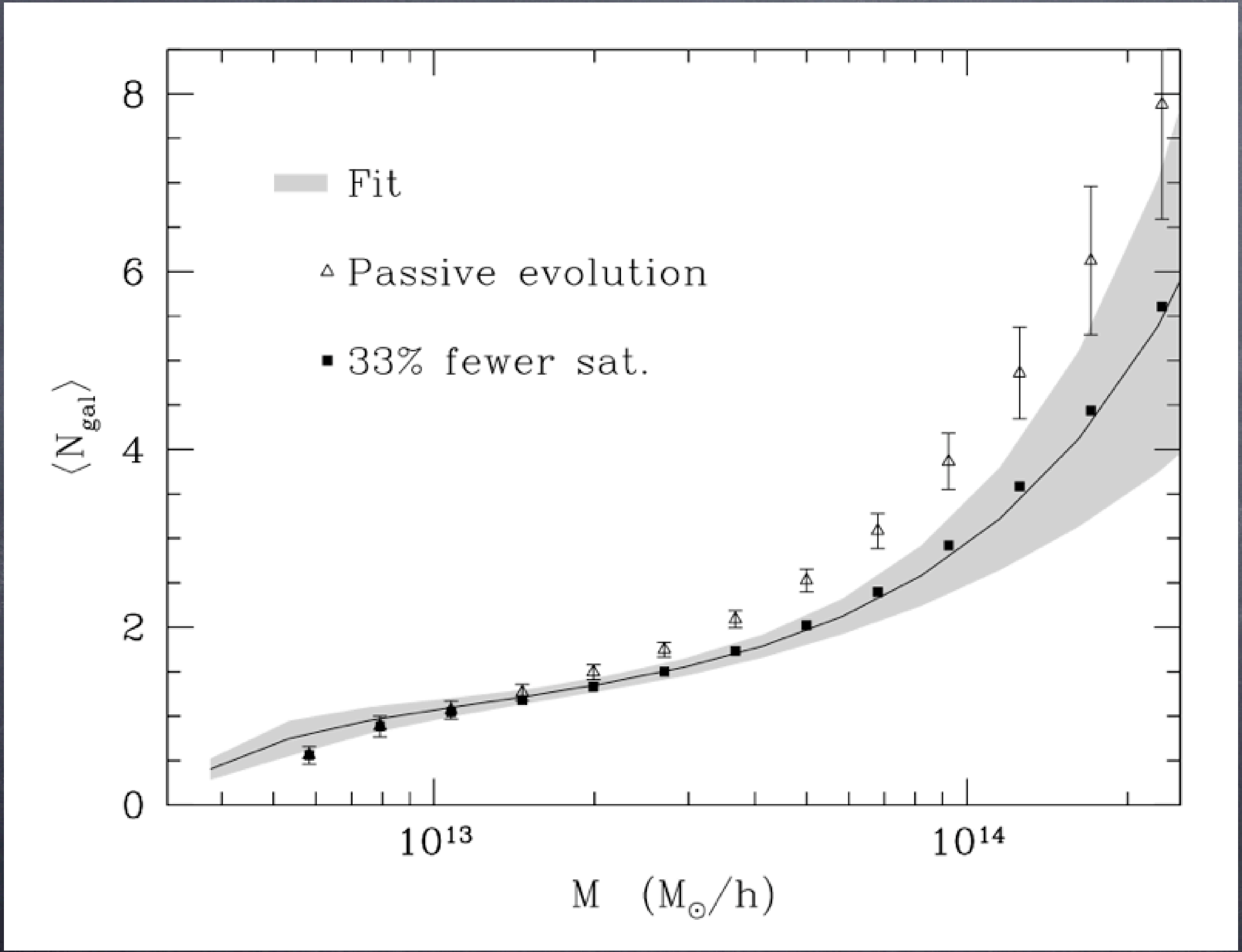
Passive evolution prediction



Populate halos at z=0.9; evolve to z=0.5 and compare

White, et al, 2007

Evidence for merging



White, et al, 2007

Summary thoughts

- Theory / Modeling
  - The Connection to Galaxies - Large Scales
  - The Connection to Galaxies - Halo Models
- Imaging vs. Spectroscopy
  - Projected density fields
  - The SDSS as a proving ground - LRGs on large scales
  - LRGs on small scales
  - QSO-Galaxy cross correlations
  - Red galaxy merging

Summary thoughts

- Where do we go from here?
  - SDSS imaging data still can be milked for a lot more science (eg. low redshift evolution of L* galaxies)
  - Next generation of imaging surveys coming on line now. Unique opportunity to learn about higher redshifts.
  - Cosmology
    - Testing the concordance paradigm
    - Baryon acoustic oscillations